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OBSERVATIONS ON STRUCTURES IN THE SLATES OF NORTHAMPTON COUNTY, PENNSYLVANIA[1]

CHARLES H. BEHRE, JR.
The University of Cincinnati

ABSTRACT

The observations which follow deal chiefly with the secondary structures in the slates of Northampton County, Pennsylvania, a portion of the Appalachian Valley. The rocks of the region include limestones of Cambrian and Ordovician age, the Ordovician Martinsburg slate, and the Silurian (?) Medina conglomerate. The general structure is a northward-dipping monocline, intensely folded and showing some faulting. Studied in detail this structure yields observations and conclusions of two types: (1) those that have a regional bearing upon Appalachian geology, and (2) those of more general interest to geologists engaged in structural work, not necessarily in the area discussed.

To the former type belong the general northward recumbent attitude of the minor folds, the very common parallelism between bedding and cleavage strikes, and the evidences for an important diastrophic epoch between Martinsburg and Medina sedimentation.

Of more general interest are studies relating to the effect of pitch of folds upon dip and strike; description of the appearance of recumbent folds in horizontal and vertical sections; an exposition of a method for restoring structure at depth when bedding and cleavage are seen at the surface; and descriptions and explanations of false cleavage and grain in slate.

LOCATION OF REGION

During the past two years a detailed study of the productive slate belt in Northampton County, east-central Pennsylvania, has been completed by the writer. Probably nowhere else in the eastern United States is structure in incompetent beds more diagrammatical-

[1] Published with the permission of the State Geologist of Pennsylvania; conclusions as to the age of the folding are those of the writer, to which the State Geologist is not committed.

ly displayed. Hence, although the prime object of these studies was economic, a brief description of the structure seen in the slate is justified.

The region described includes an area about 23 by 7 miles extending northeastward between the Lehigh and Delaware rivers. This strip of land is shown on the Allentown, Wind Gap, and Dela-

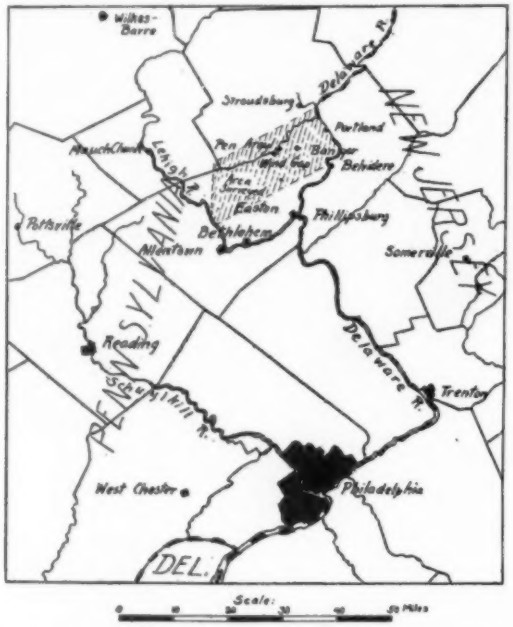

FIG. 1.—Sketch map of southeastern Pennsylvania and adjacent states

ware Water Gap sheets of the *Topographic Atlas* of the United States. A narrow strip along the east bank of the Lehigh River has not yet been studied in detail. The cross-hatching on the accompanying sketch shows the extent of the area mapped (Fig. 1).

Previous studies of the area outlined have been of a more general nature only,[1] with the exception of a detailed mapping of the Allen-

[1] H. D. Rogers, *Geology of Pennsylvania*, Vol. I (1858), various pages; R. N. Sanders, "The Geology of Lehigh and Northampton Counties," *Second Geol. Survey of Pennsylvania* (1883), pp. 83–160; T. N. Dale, "Slate in the United States," *U.S. Geol. Survey Bulletin* 586 (1914), pp. 93–104.

town quadrangle by B. L. Miller, now being published by the Pennsylvania Topographic and Geologic Survey.

GENERAL PHYSIOGRAPHIC AND STRATIGRAPHIC FEATURES

Physiography.—The region underlain by slate and here described is located in the northern part of the Appalachian Valley, within a

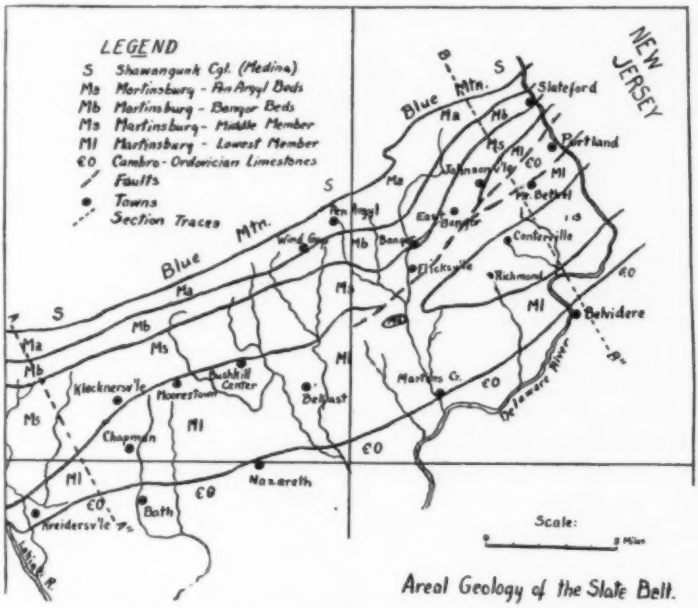

FIG. 2.—Sketch map showing areal geology of the slate belt in parts of the Allentown, Wind Gap, and Delaware Water Gap quadrangles.

narrow prong extending between the pre-Cambrian rocks at Bethlehem and Allentown on the south and the Wyoming basin on the north (Fig. 2). The northern edge of the slate belt is overlooked by Blue Mountain, which rises to a maximum height of 1,660 feet and preserves the remarkably even top that long ago tempted Davis to develop the concept of the Schooley peneplain. To the south the slate belt falls off almost imperceptibly from elevations of 800 to

600 feet. At its southern edge a drop of one or two hundred feet, distributed over a mile and hence not very conspicuous, marks a change from slate to limestone in the underlying strata.

The region has been covered by at least one Pleistocene ice sheet, which left deposits, including a conspicuous terminal moraine that extends from Pen Argyl eastward to Belvidere, New Jersey. Such glacial deposits vary in thickness and have been modified by subsequent river work.

Pre-Martinsburg stratigraphy.—The consolidated rocks encountered in a northern traverse beginning a mile south of the southern edge of the slate belt extend in age from Lower Cambrian to Silurian (?), successively younger rocks being encountered as the traverse is made northward across this large monocline. The entire sequence is shown in Figure 3; the limestones below the Jacksonburg come in contact with the slate only where the Jacksonburg has been removed by faulting.

The Tomstown, Allentown, and Beekmantown limestones represent the "Kittatinny limestone" of earlier days and extend in age from Lower Cambrian to Lower Ordovician. The age relations of these rocks have been set forth by Wherry, Ulrich, and others.[1]

Above the Beekmantown is a limestone divisible into two parts, of which the lower 75 feet are fine, even-grained black rock, not uncommonly set with bowlders derived from the underlying Kittatinny, and of Black River age.[2] The upper part is light gray to dark blue-gray, and of Trenton age.[3]

The Martinsburg formation.—Conformably above the Jacksonburg is the Martinsburg slate. As this formation in the slate district has not been previously studied in detail, a somewhat extended description is merited here. The total thickness is estimated to be

[1] G. W. Stose, "Geologic Atlas of the U.S., Mercersburg-Chambersburg folio" (No. 170), *U.S. Geol. Survey* (1909); E. T. Wherry, "The Early Paleozoic of the Lehigh Valley District, Pennsylvania," *Science*, new series, Vol. XXX (1909), p. 416; E. O. Ulrich, "Revision of the Paleozoic Systems," *Bulletin American Geological Society*, Vol. XXII (1911), pp. 27, 645; B. L. Miller, "The Mineral Pigments of Pennsylvania," *Pennsylvania Topographic and Geologic Survey Report No.* 4 (1911), pp. 18–19.

[2] Stuart Weller, "The Paleozoic Faunas," *New Jersey Geological Survey, Report on Paleontology*, Vol. III (1903), pp. 16–38.

[3] Stuart Weller, *op. cit.*, p. 37.

between 5,000 and 10,000 feet, and probably nearer the larger of these two numbers. It is readily divisible into three parts. The lowest of these is a sandy clay slate or slate, true slate being formed

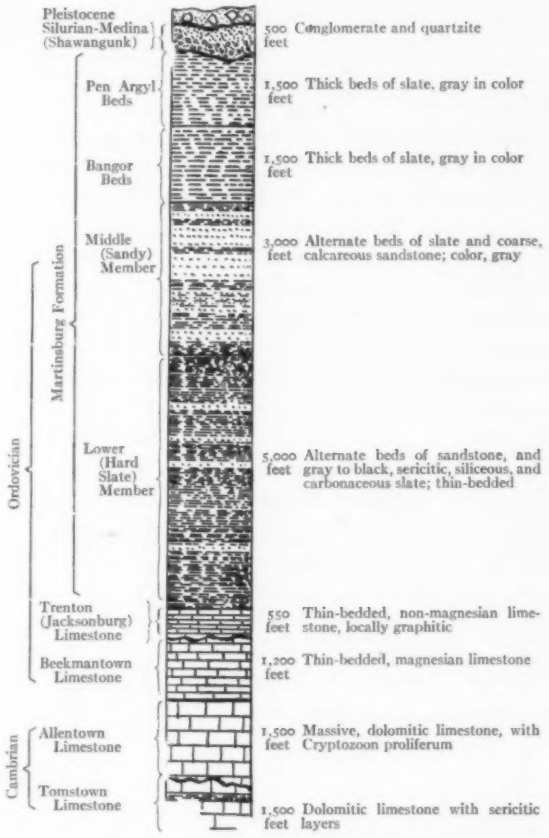
Pleistocene
Silurian-Medina (Shawangunk)
500 feet Conglomerate and quartzite
Ordovician
Martinsburg Formation
Pen Argyl Beds
1,500 feet Thick beds of slate, gray in color
Bangor Beds
1,500 feet Thick beds of slate, gray in color
Middle (Sandy) Member
3,000 feet Alternate beds of slate and coarse, calcareous sandstone; color, gray
Lower (Hard Slate) Member
5,000 feet Alternate beds of sandstone, and gray to black, sericitic, siliceous, and carbonaceous slate; thin-bedded
Trenton (Jacksonburg) Limestone
550 feet Thin-bedded, non-magnesian limestone, locally graphitic
Beekmantown Limestone
1,200 feet Thin-bedded, magnesian limestone
Cambrian
Allentown Limestone
1,500 feet Massive, dolomitic limestone, with Cryptozoon proliferum
Tomstown Limestone
1,500 feet Dolomitic limestone with sericitic layers

FIG. 3.—Columnar section of the formations of the slate belt, Northampton County, Pennsylvania.

where the sand contents have not been sufficient to prevent the development of cleavage. These beds are heavily banded and consist of alternate strata of siliceous, carbonaceous, and sericitic slate,

colored respectively light silver-gray, dark gray (almost black), and bluish gray. The separate layers are rarely more than 6 inches thick. The merchantable slate produced from this member is commonly spoken of as "hard slate" because of its relatively high silica content. Occasionally lenses of limestone, varying in thickness up to 25 feet, are seen. The thickness of the lowest nember of the Martinsburg formation is estimated at 5,000 feet. Its age is probably Trenton and Utica.[1]

The middle member of the Martinsburg formation consists of beds of sericitic slate, less completely altered clay slate, and occasional relatively thick beds of sandstone. This member is distinguished from the lower member with difficulty in isolated outcrops. Its uppermost portion consists of exceptionally thick sandy beds, generally strikingly different from those of the more slaty topmost member of the Martinsburg formation. This middle ("sandy") member is between 2,700 and 5,000 feet thick. It appears to correspond with portions of the section which in Maryland, southern Pennsylvania, and New Jersey[2] have been referred to Eden and Lorraine age.

The uppermost or "soft slate" member of the Martinsburg comprises some 3,000 feet of slate, sandy slate, and sandstone. Individual beds vary in thickness up to 20 feet, but the average is much less. Like the "hard slate" member, these beds are banded in different colors, representing variations in composition. A few strata, rich in chlorite, can be recognized by their greenish color, and thus serve as horizon markers. The sequence and relative thickness of various beds are sufficiently uniform so that correlation between beds no more than 5 feet thick can be carried as much as 4 miles along the strike. This upper member has yielded no fossils in the region described, but is almost certainly of lower Maysville age, if,

[1] J. V. Lewis and H. B. Kummel, "The Geology of New Jersey," *New Jersey Geological Survey Bulletin* 14 (1915), p. 47; R. S. Bassler, "Cambrian and Ordovician," *Maryland Geological Survey* (1919), p. 157.

[2] R. S. Bassler, "Cambrian and Ordovician," *Maryland Geological Survey* (1919), pp. 157, 167–68; G. W. Stose, "Geologic Atlas of the United States," *U.S. Geol. Survey* (1909), "Mercersburg-Chambersburg folio" (No. 170), p. 10; Stuart Weller, "A preliminary Report on the Paleozoic Formations of the Kittatinny Valley in New Jersey," *Geological Survey of New Jersey, Annual Report for* 1900 (1901), pp. 5–7.

as appears probable, it corresponds to the uppermost Martinsburg of New Jersey.[1]

For economic purposes this uppermost member of the Martinsburg can be divided in the slate belt into two nearly equal divisions, called by the writer the Bangor beds (below) and the Pen Argyl beds (above), after the type localities. In this paper no purpose would be served by a more detailed description of these two subdivisions, as they do not differ appreciably in lithology.

Medina conglomerate.—Lying unconformably on the Martinsburg shales is a well cemented, coarse quartzite, with conglomeratic layers. The formation shows cross-bedding and ripple marks. The individual beds are massive and generally 6 feet thick. Occasional thin beds of carbonaceous shale are to be seen between layers of the coarser clastics. This is the Shawangunk conglomerate, or the Medina, Lower Oneida, and Oswego of earlier writers. Its age is a moot question, Schuchert[2] regarding it as upper Ordovician (Lorraine), whereas Grabau and Ulrich[3] look upon it as Silurian. The latter interpretation is tentatively accepted by the writer.

GENERAL STRUCTURE

The major monocline.—The larger structure of the region is a northward-dipping monocline having a strike of about N. 60° E. Parallel with this structure in a general way are numerous minor folds which are most conspicuous in the slate, but can be seen also in underlying limestones where these have been exposed by quarrying, as at Catasauqua and Northampton (Allentown quadrangle).

The post-Martinsburg unconformity.—Striking in this folding are the severe contortions shown in the slate *and in the underlying limestones*, in contrast with the gentle folding in the superincumbent Medina conglomerate—a feature which has already been pointed out

[1] J. V. Lewis and H. B. Kummel, "The Geology of New Jersey," *New Jersey Geological Survey Bulletin* 14 (1915), p. 47.

[2] Charles Schuchert, "Paleogeography of North America," *Bulletin Geological Society of America*, Vol. XX (1910), p. 539.

[3] A. W. Grabau, "The Medina and Shawangunk Problems in Pennsylvania," *Science*, new series, Vol. XXX (1909), p. 415; E. O. Ulrich, "Revision of the Paleozoic Systems," *Bulletin Geological Society of America*, Vol. XXII (1911), Plate 27.

by B. L. Miller and the writer[1] and which suggests, though it by no means proves, an unconformity between the older rocks and the Silurian (?) formation. This interpretation is supported by the following facts:

1. Whereas the Medina gives evidence of one period of folding, in which open folds were developed, the Martinsburg shows two diastrophic periods—an earlier, in which the strata were folded with the development of cleavage, and a later, in which the cleavage itself was crumbled.

2. There is microscopic evidence for two periods of compression in the fact that sericite platelets which were formed during a period of intense folding were themselves crumpled by renewed pressure.

3. Pebbles of slate, apparently from the Martinsburg, are found in the basal Medina conglomerate. These have cleavage, but in two adjacent pebbles *the cleavage planes are frequently not even approximately parallel*, showing that the Martinsburg was severely folded, with the development of cleavage, *before* it was eroded to furnish a part of the material laid down in the Medina.

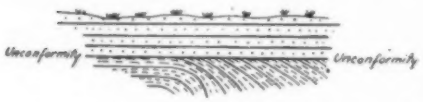

FIG. 4.—To illustrate how severely folded beds below an angular unconformity may be locally parallel to the superincumbent strata.

4. Where observed, on the east side of the Lehigh Gap, there is a divergence of 9–12° in the dip of the Martinsburg and the Medina, and of 15 in the strike, and a 30-inch zone of unusually heavy conglomerate occurs at the base of the younger formation.

It is true that localities have been mentioned elsewhere at which the Martinsburg and the Medina appear to be conformable. However, although one swallow does not make a summer, one instance of angular unconformity strongly suggests a diastrophic epoch. If the folding has been sufficiently severe between the time of formation of the earlier deposit and that of the later to make the folds of the first strata locally recumbent, then the beds of the Martinsburg

[1] B. L. Miller, "Taconic Folding in Pennsylvania" (abstract), *Bulletin Geological Society of America*, Vol. XXXVI (1925), p. 157; C. H. Behre, Jr., "Taconic Folding in the Martinsburg Shales" (abstract), *Bulletin Geological Society of America*, Vol. XXXVI (1925), p. 157.

might well be almost parallel with those of the Medina, except near the axes of the earlier folds. These relations are illustrated in Figure 4.

These considerations, coupled with the northward dip observed in the Medina conglomerate, lead to the inference that the region has been affected by two periods of larger diastrophism: an earlier post-Martinsburg and pre-Medina one, and a later one of post-Medina

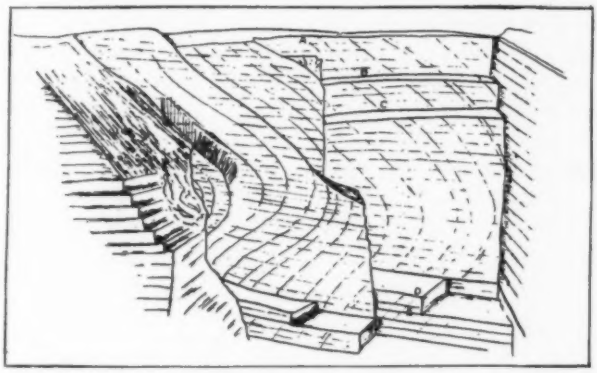

FIG. 5.—Folding seen in northeast wall of the Albion quarry, Pen Argyl. The fold is a recumbent syncline, viewed along the strike. The nearly horizontal lines are cleavage traces; their gentle curvature is well shown on Levels *B* and *C*. Letters refer to stations where thickness measurements were taken (see Table I). Depth of quarry, about 300 feet.

time—the Appalachian revolution of the late Permo-Carboniferous. No more recent major deformations, similar to the faulting so generally associated with the Newark series and traceable to later orogeny, have been identifiable.

DETAILED STRUCTURE

FOLDING

General aspects.—The minor folds developed in the region, and studied especially in the Martinsburg formation, are never symmetrical, and are rarely open. They show northward overturning, frequently to so marked a degree that the south limb of what was once an anticline is horizontal or dips gently north, while the north

limb has steep southward dips. With such folding only an application of the working principle that the cleavage parallels roughly the axes of the folds will explain the feature shown in small and isolated outcrops.

Thickening and thinning in folds.—Moreover, especially in the lower members of the Martinsburg, where thick competent strata are missing, the limbs of the folds are very closely apposed (opening angles measuring as little as 9°) and are in many instances so nearly parallel as to conceal the presence of the fold unless the eye happens to alight upon the sharp curve of a bed near the axial plane. This type of folding is necessarily accompanied by considerable thickening and thinning.

TABLE I

COMPARISON OF THICKNESS OF PEN ARGYL GRAY BED IN THE ALBION QUARRY

Observation Point	Depth below Surface (feet)	Dip of Bedding	Thickness of Bed (Inches)
A	0	27°S.	54
B	85	28.5°S.	80
C	120	35°S.	79
D	275	19°N.	112
E	285	9°N.	113

In the upper member of the Martinsburg, however, the thickening and thinning are not at all conspicuous, because of the fact that the folds are not extremely "tight" (opening angles not less than 42°). Nevertheless considerable variation is observed in the thickness of the beds as the troughs are approached. This feature is well shown in quarry walls, where the actual thickness can be measured. Thus, in the Albion quarry at Pen Argyl, the strata are thrown into a syncline, the axial plane of which has a gentle southward dip. A single bed was carefully measured here at various depths, both above and below the axis, with the results shown in Figure 5.

These figures not only suggest a thickening at the axis, but a greater thickness on the north than on the south limbs of synclines—which is to be expected in northward recumbent folds, especially if the folds rise to the south and have axial planes dipping southward. The same results are obtained in a series of measurements of another

bed made at Bangor in three quarries which expose different parts of the same fold (see Fig. 6).

TABLE II

COMPARISON OF THICKNESS OF BANGOR GRAY BED IN THREE QUARRIES

Observation Point	Dip of Bedding	Thickness of Bed (Inches)
A	20°S.	26
B	44°N.	110
C	23°N.	53

Northwestward overturning.—It is, of course, a well-demonstrated principle that the folding in the Appalachian region shows northward overturning. In the slate, however, where a great thickness of rocks, not readily correlated from place to place, is seen, and where the axial planes are generally horizontal, the overturning must be inferred, at least to some extent. Here and there sedimentary features,

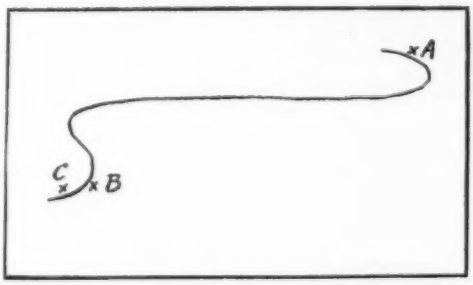

FIG. 6.—Vertical section (composite diagram) of folding in several quarries at Bangor, to show attitude of beds and stations at which thickness measurements were taken (see Table II).

such as ripple marks (see Fig. 7) and cross-bedding, but yet more strikingly the subaqueous erosion of a clay bed before the laying down of a sandy layer or the sequence (sandy beds with irregular lower surface, becoming finer upward and grading into argillaceous sediments), furnish a clue to as top and bottom of beds, even if the bedding-cleavage relation, so well developed by Leith[1] as a means for

[1] C. K. Leith, *Structural Geology*, revised ed. (New York, 1923), pp. 181–83.

determining superjacence, be neglected. In the folds actually observed in the slate there is also a constant northward overturning. In no instance, even in the most complex and incompetent beds, is the overturn to the south. This is shown even in detailed sections. The figures illustrate these relations (Figs. 8–11).

Although the writer finds it difficult to agree with the conception of a simple northeastward thrust against the Appalachian geosyncline from the continental borders, this feature of constant northward overturn does certainly make it appear that the moving force inducing the overturn came from the southeast. The only other explana-

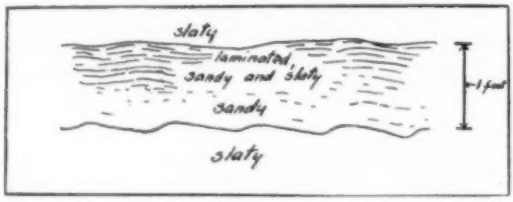

FIG. 7.—Sketch diagram of bedding as seen in southeast wall of Bangor Vein (Peerless) quarry, East Bangor. Throughout the slate region, cross-bedding and ripple marks show that the currents came from the east. In this vertical section the beds are completely overturned, so that the sandy ripples have their gentler sides toward the west.

tion which might be offered would be the reflex overturn *toward* the direction of the moving force when drag is developed on that side of the anticline that is nearest the applied force, thus producing a sort of under-rolling of such a nearer limb. This effect, though illustrated by Willis's well-known experiments,[1] cannot well be appealed to in face of the heavy overburden assumed to have been above the Martinsburg shales at the time of deformation.

Pitch of folds.—Many folds have a pitch, either northeast or southwest. This is generally not conspicuous, the angle of the cleavage (which roughly parallels the axial plane of the fold) generally being parallel in strike with the beds. In some instances, however, there is a notable divergence. At East Bangor, for instance, a westward pitching syncline is exposed in the quarries of the East Bangor

[1] Bailey Willis, "The Mechanics of Appalachian Structure," *U.S. Geol. Survey, 13th Annual Report*, Part II (1893), Plates LXXXIII, LXXXV, LXXXVII, etc.

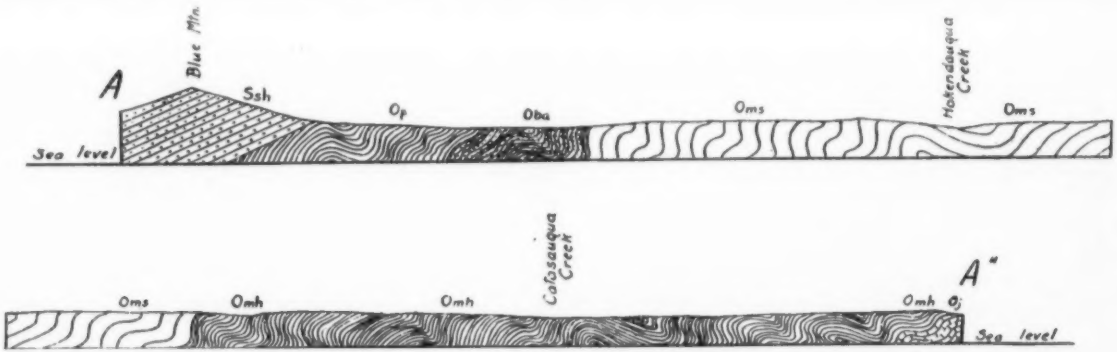

FIG. 8.—Structure section through slate region along *AA"* (see Fig. 2). Scale, 1½ inches per mile. Legend, *Ssh*, Shawangunk conglomerate; *Op*, Pen Argyl beds; *Oba*, Bangor beds; *Oms*, middle member, Martinsburg formation; *Omh*, lower member, Martinsburg formation; *Oj*, Jacksonburg limestone.

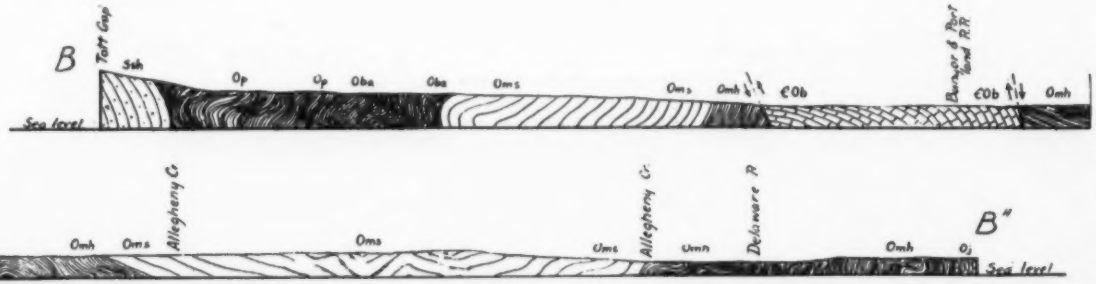

FIG. 9.—Structure section through slate region along *BB"* (see Fig. 2). Scale, 1½ inches per mile. Legend as above; *COb*, Cambro-Ordovician limestones.

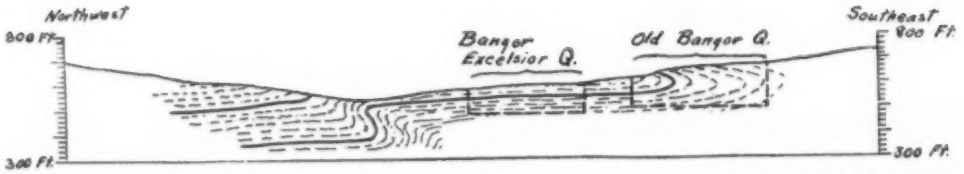

FIG. 10.—Detailed structure section at right angles to strike through Bangor Excelsior and Old Bangor quarries at Bangor. Bearing of section, about N. 30° W. Horizontal and vertical scale, 1 inch = 700 feet. Solid lines indicate horizon-marking beds.

FIG. 11.—Detailed structure section about parallel to strike of general structure at Pen Argyl; section cuts Albion quarry, trending approximately N. 60° E. Horizontal and vertical scale as above. Conventions as in Figure 10.

Consolidated Slate Company (see also map of region, Fig. 2). Again, a westward pitch is seen at the Bangor Superior quarry at West Bangor.

An unusual type of pitch is observed in folds having horizontal or only slightly inclined axial planes. In such instances the *pitch* is represented by a northward swing of the synclinal trough or a southward swing of the anticlinal crest. To define such a structure it is best to develop the concept of the "axial line," which may be described as the intersection of the axial plane with any given bed in the trough or crest of the fold. Accepting this definition the geologist may describe the appearance of typical pitching recumbent folds in the slate by saying that a vertical projection of the axial line upon a horizontal plane would be represented by a curved line (Fig. 12). On vertical planes, such as quarry walls, drawn through the strike of the axial planes of such folds, the traces of the beds will appear as ellipses, which are, in most cases, flat. An illustration is afforded by a sketch of the bedding in the Columbia Bangor quarry's northwest wall (Fig. 13), though the effect is here heightened by the fact that this syncline and the quarry wall intersect at a gentle angle anyway —a common enough feature in the slate quarries.

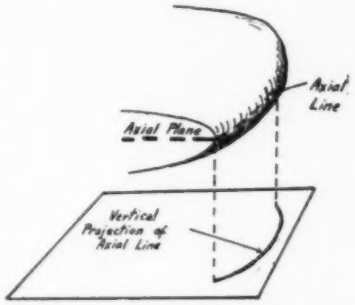

FIG. 12.—To illustrate method of expressing pitch in a doubly pitching structure having a horizontal axial plane: the curved axial line is projected upon a horizontal plane of reference.

Effect when nearly horizontal axial planes are gently tipped.—Another unusual form which pitch assumes in connection with folding is observed at the American Bangor quarry. This is a large opening about midway between Bangor, Pen Argyl, and Ackermanville, and 1½ miles from each. Deserted since 1914, it is partially filled with water and inaccessible at depth. At the surface the beds have an average strike of N. 65° E., and dip 15–30° S. The cleavage has a similar strike, but dips only 8° S. The relations indicate that the

quarry is opened in the north (lower) limb of an anticline the axial plane of which dips south, probably at an angle of about 8°. Some 500 feet westward along the bedding strike is the Bangor Southern quarry, also filled with water and showing only about 20 feet of bed rock. In these 20 feet the beds strike uniformly N. 57° E.; the dip is 31° N. at the north end of the quarry and declines to 20° N. at the south end. At a depth of 180 feet the beds turn, dipping south, the

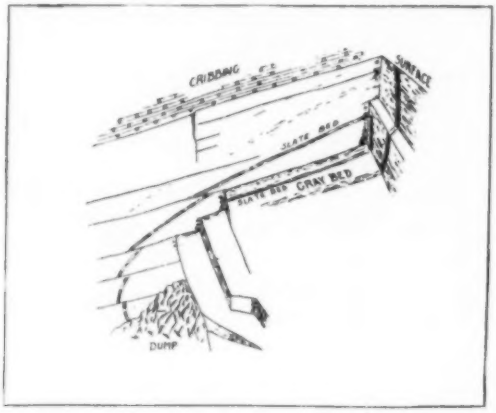

FIG. 13.—Sketch of north corner of Columbia Bangor quarry, Bangor, as seen when looking down into corner from southeast side at surface. Shows semi-elliptical trace of a bed in the slate on the quarry wall; this effect is produced by the curvature of the axial line in the horizontal plane. Depth of dump in the quarry is about 125 feet below the surface.

quarrymen say. The cleavage strikes uniformly N. 65° E. and dips 20° or less to the south. When this structure is compared with that in the American Bangor quarry it is seen that the beds in the Bangor Southern show the south or upper limb of the anticline of which the lower limb is seen in the American Bangor opening. In short, the axial plane of the structure dips westward. This interpretation is further supported by the fact that the beds possess a more northerly strike than does the cleavage (or axial plane of the fold) in the western quarry. Such structural relations are shown in Figure 14, to the right.

The example and diagram given explain why, in a fold with almost horizontal axial plane, a slight tilt of the plane may cause the strike and the angle and direction of dip of an exposed bed to show marked changes along the outcrop within short distances.

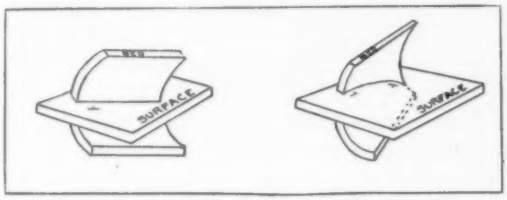

FIG. 14.—Block diagrams to show effect of pitch on the strike and dip of beds exposed at the surface in the case of recumbent folding. Left, strike and dip constant all along the surface of the ground because axial plane of fold is horizontal; right, strike and dip of bed both varying along the outcrop because axial plane of fold declines downward toward the left of the diagram.

Shortening by folding.—Various estimates of crustal shortening in the northern Appalachians have been made.

TABLE III

EARLIER ESTIMATES OF CRUSTAL SHORTENING IN THE APPALACHIAN REGION

Ratio before and after Compression	Estimate Made by	Reference	Shortening Measured at	Shortening (Miles)
2.35:1 . . .	E. W. Claypole	*Amer. Nat.*, Vol. XIX (1885), pp. 257–68	Appalachians in Pennsylvania	153 to 65
1.22:1 . . .	R. T. Chamberlin	*Jour. Geol.*, Vol. XVIII (1910), pp. 230–37	Tyrone to Harrisburg, Pa.	81 to 66
6:1	F. B. Peck	*Pa. Geol. Survey, Report No.* 5 (1911), p. 39	Catasauqua, Pa.	6 to 1
2.12:1 . . .	F. B. Peck	*Econ. Geol.*, Vol. III (1908), p. 54	Martins Creek, N.J.	8.82 to 4.16
1.66:1 . . .	Arthur Keith	*Geol. Survey Amer. Bull.*, Vol. XXXIV (1923), p. 335	General estimates	500 to 300

These estimates, taken over various lengths of exposure, agree in a general way in placing the ratio of undeformed to compressed crust at about 2:1. Estimates in the slate lead to smaller ratios, though the lengths of exposure studied vary greatly.

The localities to which these figures apply were selected because they showed no faulting, but appeared to give fairly complete exposures on which restorations could be based. The general agreement of the resulting figures certainly justifies the conclusion that an average would represent the approximate shortening within the Martinsburg formation. As this is probably the most plastic member of the Appalachian Paleozoic series, it seems not unlikely that the results obtained represent the maximum of crustal shortening in the Appalachian valley of southeastern Pennsylvania.

General conclusions.—All of the folding observed, in its closeness, the marked thickening and thinning of individual beds, and the

TABLE IV

SHORTENING OF SLATE STRATA AS MEASURED IN NORTHAMPTON AND LEHIGH COUNTIES, PENNSYLVANIA

Location	Shortening	Ratio, before and after Compression
Railroad, Siegfried to Rockdale	30.5 to 25 feet	1.22:1
Railroad, Siegfried to Rockdale	142 to 110 inches	1.29:1
Old Bangor and Bangor Excelsior quarries	2,125 to 1,880 feet	1.13:1
Section across slate belt	4.55 to 4.10 miles	1.11:1
Section across slate belt	2.5 to 2.07 miles	1.20:1

pitching of the folds, both in the horizontal and vertical planes—all of this folding indicates clearly the behavior of rather uniformly plastic matter adjusting itself irregularly in the manner to be expected when a thick mass is deformed. In the Green Mountain region of Vermont, Dale[1] has described folding which is similar in most respects to this in Pennsylvania, with the notable exception that the prevailing bedding strike in the Pennsylvania region is N. 60° E., whereas that in the Vermont–New York district is generally about due north, though locally variable.[2]

[1] T. N. Dale, "Structural Details in the Green Mountain Region and in Eastern New York," *U.S. Geol. Survey Bulletin 195* (1902), pp. 1–12.

[2] T. N. Dale, "On the Structure of the Ridge between the Taconic and Green Mountain Ranges in Vermont," *U.S. Geol. Survey, 14th Annual Report*, Part II (1894), pp. 531–49; T. N. Dale, "The Slate Belt of Eastern New York and Western Vermont," *U.S. Geol. Survey, 19th Annual Report*, Part III (1899), pp. 192–99, Plates XL and XLI.

CLEAVAGE

Prevailing strike and dip.—In general the strike of the cleavage is like that of the beds, about N. 60° E. In attitude, however, it differs from the bedding in that the dip is far lower—ordinarily about 20°—and usually southward.

Relations between axial planes of folds and cleavage.—There has been considerable discussion as to the arrangement of cleavage with regard to the axes of folds. In American literature Van Hise[1] credits

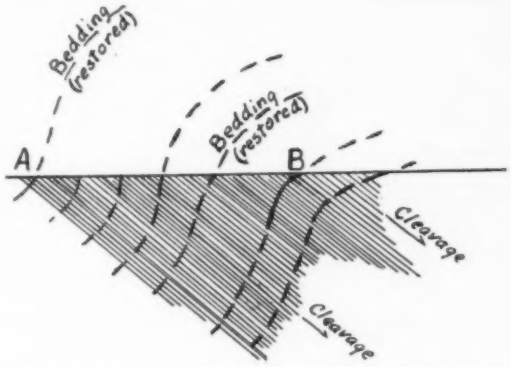

FIG. 15.—To show method of restoring structure at depth. Bedding and cleavage are exposed at *A* and *B*; bedding dip is assumed to be the same wherever bedding crosses a given cleavage plane.

Pumpelly with pointing out the general parallelism of the axes of folds and of the planes of secondary cleavage. Although parallelism in strike is a generally accepted feature, there need not necessarily be an agreement of the *dips* of axial and cleavage planes. Dale[2] cites instances in which the cleavage inclines inward toward the axial planes near the crest of anticlines. Heim,[3] too, figures a case of this type. If the cleavage actually converges toward the axis in this fan-

[1] C. R. Van Hise, "Deformation of Rocks," *Journal of Geology*, Vol. IV (1896), p. 349.

[2] T. N. Dale, "Slate in the United States," *U.S. Geol. Survey Bulletin* 586, (1914), p. 35.

[3] Albert Heim, *Geologie der Schweiz*, Band II (Leipzig: Tauchnitz, 1921), p. 81, Fig. 31.

like manner any single cleavage plane must be faintly curved. This concept will be referred to again in relation to the question of the observed curvature of cleavage.

Method of restoring folds.—In the region here described the cover is thick and exposures are relatively few and isolated. Yet where exposed the bedding can generally be distinguished. What outcrops can be found must be virtually squeezed dry to yield their hidden bearing on the structure in the immediate vicinity. In such inter-

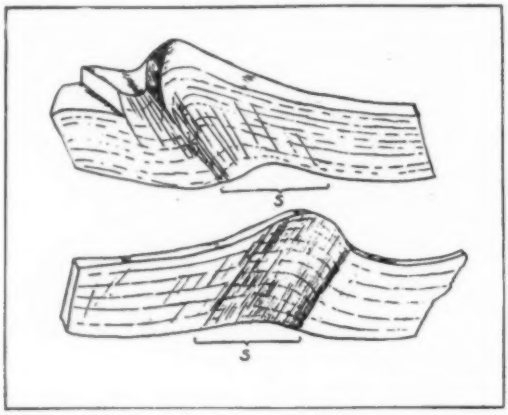

FIG. 16.—Two views of small block of slate 5 inches long. Top and bottom are cleavage planes, secondarily crinkled. Cracks, almost vertical, generally parallel, and especially closely spaced at *S*, are fracture cleavage, developed incidentally to the folding of the true cleavage. Bedding not visible, but actually almost parallel to the true cleavage planes.

pretations it was assumed—and this appeared fully justified by what could be seen in the quarry walls—that the cleavage planes are approximately parallel to the axes of the anticlines and synclines, the folding being of the "similar" type. It is, then, certainly a reasonably accurate assumption that along a given cleavage line the angle between bedding and cleavage will be the same. In this way it is possible, from a few rather isolated exposures, to restore the structure, at least in the upper member of the Martinsburg, in which the folds are relatively open and large. This method of restoration is explained diagrammatically in Figure 15.

Constancy in cleavage strike and dip.—Although there were observed numerous instances in which the strike of the cleavage differed locally from that prevailing over the region as a whole, there is generally a remarkable constancy in strike, the usual bearing being N. 50°–80° E. The dip too is almost invariably southward. In those instances where the dip is to the north, the angle is very small, as though the northward inclination were due purely to a tilt of the cleavage planes during their formation—the planes having apparently been gently rotated through the horizontal and into a slight northward dip. Such cases are probably parts of a gentle curvature of the cleavage, like that described in the second paragraph following.

Curved cleavage.—In places, however, the cleavage is strongly curved or even crumpled in such a way as to suggest movements

FIG. 17.—Folded cleavage flake of slate. Flat top surface is cleavage plane

secondary to its complete development. This observation confirms the impression of two periods of post-Martinsburg folding already mentioned. Illustrations are given in Figures 16 and 17.

There are, however, instances in which gentle curvature of the cleavage is distributed over wider areas and is frequently observable within a single fold, as in the case of the Albion quarry (see Fig. 5), in which the cleavage dips gently southward for the most part, but has a slight northward inclination along the northwest part of the opening. The north dip appears to be incidental to cleavage development, not induced by subsequent deformation.

FALSE CLEAVAGE

Description.—In beds of thin slate between layers of sandstone, especially in the middle ("sandy") member of the Martinsburg formation, the cleavage surface shows fine fissures, short and inconspicuous, forming planes generally at right angles to the cleavage planes but having strikes parallel to the latter (see Fig. 16). Slate so

affected breaks into slender pencils under the hammer. These fine fissures correspond genetically to the "fracture cleavage" of Van Hise or the "slip cleavage" of Dale. Under the microscope they are seen to be due to minute plications of the true cleavage planes, an observation agreeing with the earlier ones of Dale.[1] When the plicating process has proceeded to a certain stage, rupture follows, producing the clefts noted. Frequently the little false cleavage planes bear the same relation to folds in the true cleavage that true slaty cleavage bears to the folds of the bedding.

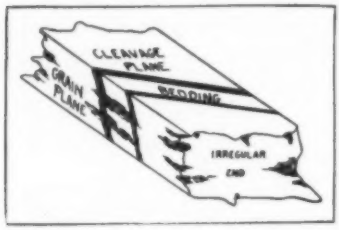

FIG. 18.—Structural features in a block of slate as quarried: to show relations between grain, cleavage, and bedding planes. Bedding may intersect cleavage at any angle, but grain and cleavage planes are at right angles to each other.

Age relation of false and true cleavage.—The fact that false cleavage is generally parallel to true cleavage might be interpreted by some geologists as indicating that the two were simultaneously developed.

There is every evidence in the slate district to suggest that this false cleavage is a later development than the true cleavage: it is associated with microscopic crinkles in the latter; it is frequently developed where slips between bedding have taken place; it is seen in places where the true cleavage is megascopically badly folded. These observations are in agreement with the conclusions of Leith.[2]

Even without considering other evidence in favor of two epochs of diastrophism, the false cleavage relations alone suggest that there were two separate periods of deformation. From the observations previously set forth above it is clear that the appearance of false cleavage is subsequent to the development of true cleavage in the slate. The earlier diastrophic epoch is thus represented by the true cleavage, the later, by the false cleavage.

The general parallelism in strike of false and true cleavage is to be attributed to similarities in the direction of thrusts acting in the two orogenic epochs.

[1] T. N. Dale, "The Slate Belt of Eastern New York and Western Vermont," *U.S. Geol. Survey, 19th Annual Report* (1899), Part III, Plate XXVIII.

[2] C. K. Leith, "Rock Cleavage," *U.S. Geol. Survey Bulletin 239* (1905), p. 120.

GRAIN

Description.—In quarrying slate there are generally observed two planes of easy parting, one being the cleavage and the other a plane at right angles to the cleavage and called by the quarrymen the "grain," "sculp," or "scallop" (see Fig. 18). It is scarcely distinguishable by any megascopic feature in the unbroken slate, but if the slate is fractured, a line of parting develops across the cleavage, standing (in the district described) vertically, and frequently so well marked as actually to form the quarry walls. Microscopically it is seen that sericite flakes and other mineral particles with three unequal dimensions have their longest axes parallel to the strike of the grain plane.

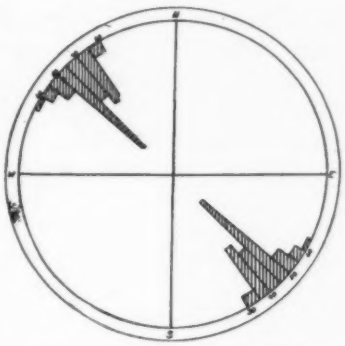

FIG. 19.—Azimuth diagram of strikes of grain in seventy-one quarries, selected at random. Almost all observations lie between N. 35° and 50° W.

It is a noteworthy fact that the grain plane has a very constant strike. This is shown by Figure 19. In not a single case was the grain strike observed to fall outside the limits indicated in the figure. As the sides of the quarries are generally developed along the grain plane, a mere glance at a map showing the orientation of the quarries serves to emphasize the constancy of the grain strike.

Origin.—In the opinion of the writer, grain was developed synchronously with cleavage, and is a response to the vector elements of the pressure to which the clays were subjected in their first folding.

If, in the interests of simplicity, the deformations here seen are pictured as being produced by compression in the superficial layers of the earth's crust, the forces acting on the shaly beds might be resolved into three directions: (1) the tangential direction parallel to the direction of major thrusting, (2) the tangential direction at right angles to this, and (3) the direction of gravity, which tends to op-

pose the upward bulging of anticlines. As folding resulted and as a general trend of N. 60° E. may be recognized in the fold axes, the force in direction 1 was clearly stronger than that in directions 2 and 3. Had the pressure in direction 3 been greater than that in direction 2, the folds should show vertical axial planes; they do not, hence the force acting in direction 3 was weakest. It is clear, then, that if secondary crystals (such as those of sericite and chlorite) show elongations proportional to the forces acting at right angles to such elongations, their longest dimensions will be parallel to the cleavage dip, their shortest, approximately perpendicular to the cleavage dip, and their intermediate lengths at right angles to the grain strike.

Explanation of constancy in grain strike.—The question may be raised, Why, despite the development of crumpling of the slaty cleavage and the not infrequent change in its strike from the original bearing of about N. 60° E., did the *grain* strike maintain its constancy? The answer is twofold. In the first place, the later (Appalachian) thrusting was directed similarly to the earlier (post-Martinsburg) thrusting, as has already been suggested in the description of false cleavage. Secondly, the grain planes, veing *vertical*, suffered but little change in strike even when the direction of thrust was slightly altered, whereas the cleavage planes, being but slightly inclined to the horizontal, had their strikes severely changed where the horizontal component of pressure was no longer directed exactly as it was while the cleavage was forming.

FAULTING

Faulting is not a conspicuous phase of the regional structure. It is of common occurrence, however, and of three types: (1) thrust-like faults of large extent; (2) normal faults, having small displacements and showing over small areas only; (3) bedding-slip faults.

Thrustlike faults of large extent.—Two such faults were found (see Fig. 2). The northern enters the district at Delaware River, about nine-tenths of a mile south of Slateford, and extends S. 45° W. for a distance of about a mile, until it is lost under the terrace gravels 2 miles west of Portland. Its eastward continuation is seen on the New Jersey side of Delaware River, 1 mile west of Hainesburg (Delaware

Water Gap quadrangle). The vertical throw here is at least 1,850 feet. The dip is probably southward and gentle, but is not actually shown. The eastward continuation of the fault has been described by Kummel.[1]

Half a mile south of Portland, on the west side of the Delaware River, is another fault, the eastward continuation of which, too, has been mapped by the New Jersey Geological Survey. This fault brings the Lower Jacksonburg against the Lower Martinsburg, the upthrow being to the north and probably not exceeding 500 feet in vertical displacement. This may well be a normal fault, but positive evidence is lacking, as the dip of the plane is completely concealed.

Normal faults of small displacement.—In several quarries smaller faults are exposed or may be inferred from the displacement of recognizable slate beds. These faults strike about due north, with variations of 30° either way, and dip gently (25–30°) east. In most cases the faults cut beds approaching verticality and the movement appears to have been partially horizontal, as though one segment of the fold had moved north horizontally. Such movements are unquestionably coupled with a slight vertical displacement as well. In general, the hanging wall has moved north.

Such faults may be explained in one of three ways: First, they may be of post-Triassic age, like the faulting of the Newark series, and not clearly related dynamically to the earlier folding and faulting of the region. Second, they may represent relaxations after the compression which produced the folding of the post-Ordovician or post-Carboniferous orogeny. Or third, and most probably, they may represent compression breaks parallel to the general direction of thrusting, the blocks defined by them moving forward slightly with regard to neighboring blocks.

Bedding-slip faults.—These are faults which cut across the beds at small angles both to the strike and to the dip of the bedding. They are generally developed in localities of close folding. They appear to represent an adjustment incidental to further compression of the folds.

Age of faulting.—In the writer's opinion all of these faults are

[1] H. B. Kummel, "Report on the Portland Cement Industry," *New Jersey Geological Survey, Annual Report for 1900* (1901), pp. 63–65.

later than the development of the slaty cleavage. Where they are developed the cleavage is commonly badly crumpled. Moreover, being fractures, they point to a brittle condition of the slate somewhat different from that postulated during cleavage development. Many of them are definitely related to systems of joints which are largely open. They would seem to be of the same age as the false cleavage already described.

RECENT HORIZONTAL OFFSETS ALONG THE HAYWARDS FAULT

RICHARD JOEL RUSSELL
University of California, Berkeley, California

ABSTRACT

The character of stream offsets along the Haywards fault throws light upon the nature of horizontal displacements taking place on that line.

The Haywards fault parallels San Francisco Bay on its eastern side. For thirty miles or more it is situated at, or near, the southwestern base of a long and comparatively low range of hills, commonly known as the Berkeley Hills. These are the northwestern end of a long northwest-southeast range known as the Mt. Hamilton Range, of central California.

Lawson describes the geology of the Berkeley Hills in the San Francisco Folio of the *Geologic Atlas of the United States*. In his text the Haywards fault is briefly described and its approximate location is shown in two text figures, but it is a curious fact that in his map of areal geology the delineation of this important feature is almost wholly omitted.

While the trace of the Haywards fault throughout most of its extent is situated at, or near, the base of the Berkeley Hills, it is not altogether certain that the hills have grown as a result of movement upon this particular plane of rupture. Here and there the trace, which can be followed quite continuously along various aligned drainage features, sag ponds, saddles, and other rift features, passes upward along the front of the hills or out into the comparatively flat Bay Plain below, departing in its local strike from that of the hills themselves. For some three or four miles near the northwestern end of the Berkeley Hills the fault evidently approximates the crest of the hills, some 500 or 600 feet above the elevation of the adjacent Bay Plain. Where the fault thus leaves the base of the hills it is apparent that agencies other than uplift along the Haywards

fault are responsible for the more or less constant state of erosional rejuvenation observed on the southwestern front of the hills.

Though the relationship between the Haywards fault and the elevation of the Berkeley Hills is probably quite obscure, the relationship of that line to relatively recent horizontal displacements is striking. In this connection Lawson states:

> The streams on this (southwestern Berkeley Hills) slope originally flowed with steep gradients across a zone of marked deformation and faulting and were relatively straight. Later faulting along the old fault zone apparently offset to a small extent some of these streams, and other streams were deflected along the line of the fault in a longitudinal rift valley that was formed in part directly by faulting but chiefly by excessive erosion of the zone of crushed and mashed rock produced by the faulting.[1]

FIG. 1.—Typical stream offset on the Haywards fault

In a 9-mile stretch, centrally located on the fault between the towns of Haywards and Niles, the writer found all streams and gullies, with the exception of a few which have been very recently formed clearly as a result of agricultural operations, offset horizontally in such a way that the Bay-Plain block, southwest of the fault, has moved toward the northwest with reference to the Berkeley Hills block on the other side of the fault. A small offset of this nature is shown in Figure 1.

[1] A. C. Lawson, *U.S. Geol. Survey Atlas*, Folio 193 (1914), p. 21.

At places the zonal nature of the fault is well shown in these offsets, which often occur one above the other in a zone having a width of as much as a quarter of a mile. Streams are commonly offset two or three times in crossing the fault zone. While the fault zone quite commonly extends for some distance up the front of the hills, it is generally true that the largest stream offsets are found near the base of the hills and that higher up the indicated displacement is less.

The offset appearance found in the streams crossing the Haywards fault might well be paralleled by streams developed as minor subsequent features, reflecting structural control, in a region of stratified rock. In the area under consideration such control is generally wanting, and the offset features pass through massive rhyolite bodies, massive sandstones, and across stratified rocks at various angles to their strikes. The offset features occur at such short intervals that one is able to line them up precisely and to trace out several lines in the fault zone with a high degree of accuracy. These lines are clearly unaffected by rock structures exposed at the surface.

The exact amount of displacement at each offset is something that cannot well be measured with absolute accuracy. A close approximation to the displacement is possible, however, because practically all of the small streams concerned flow in quite sharply notched channels and the channel centers can be used as points between which measurements are made. Displacements thus measured vary between 25 and 600 feet. While it may be possible to demonstrate, on the basis of petrographic evidence, that the total displacement has far exceeded any figure of a few hundreds of feet, and while it is certain that stream offsets themselves indicate greater values along other portions of the Haywards fault, the value of 600 feet was the largest found in the 9-mile stretch between Haywards and Niles, the area studied in most detail by the writer.

A distinct correlation exists between the amount of offset and the size of the stream involved. Sixteen small streams and gullies, mostly less than a mile long and confined to the first front of the hills, are offset 200 feet or less. Ten larger streams, mostly from 1 to 5 miles long and extending back of the first hill crests, are offset

from 200 to 600 feet. This relationship is interpreted to mean that horizontal movement has been taking place for a considerable length of time. Streams formed at an early date have shared in a greater number of individual displacements than have those more recently formed. While an exact size-age correlation could certainly not be expected it is nevertheless certain that the small streams, offset but 25, 50, or even 100 feet, are very recent in origin as compared

FIG. 2.—Offset stream with the portion of its channel southwest of the fault abandoned.

to the larger and more strongly offset streams which have developed rather large drainage basins extending quite deeply into the hills.

Only three out of twenty-six streams were forced to abandon the portions of their channels southwest of the fault zone. In general the rate of horizontal movement seems to have been sufficiently slow, and displacements occurred in sufficiently small steps so that even small intermittent streams have been able to maintain their channels across the lines of displacement. In three cases, one of which is shown in Figure 2, the task proved too great for the streams, and new straight courses were developed directly below the offsets. In these cases the abandoned channels exist as valleys without headwaters, and are always some distance northwest of their pre-offset positions. The fact that streams have been thus be-

headed as a result of horizontal movement indicates that, though in the main the displacement has been slow and by small steps, an individual movement may take place rapidly and may be of such magnitude that the portion of a notch or channel on one side of the fault is entirely shoved past the portion on the other side.

Additional evidence of horizontal offsetting is furnished by the alluvial fans which the streams are building on the Bay Plain below the fault. The larger fans are noticeably flat-topped and the streams invariably flow along their southeastern sides. It thus appears that the fans are being moved toward the northwest during their growth. It is only in the cases of the smallest fans, or recently formed cones, that any approach to areal symmetry is to be found.

From the preceding evidence it is apparent that the type of horizontal movement taking place on the Haywards fault is such that earthquakes would result from individual displacements. That such movement is taking place at the present time is borne out by the fact that earthquakes attributed to the Haywards fault are very frequently recorded on the seismographs at the University of California stations at Berkeley and at Mount Hamilton. The last great earthquake attributed to movement on this particular fault took place in 1868, when the town of Haywards and several villages and towns in its vicinity suffered heavily.

It is interesting to note that the direction of displacement on the Haywards fault agrees with that which took place on the San Andreas fault, on the western side of San Francisco Bay, when in 1906 the block southwest of the fault was shifted as much as 21 feet toward the northwest relative to the area on the other side of the line.

The writer believes that further study in the Coast Ranges of central California will reveal many interesting geomorphic features related to horizontal offset along the numerous parallel faults of which the Haywards and the San Andreas are probably the best known representatives. His knowledge of such features on several of these lines leads him to the belief that it will generally, if not always, be found that the direction of displacement has been such that the block southwest of each fault has been moving northwest with reference to the block on the other side of the break.

THE USE OF CALCULATIONS IN PETROLOGY: A STUDY FOR STUDENTS

FRANK F. GROUT
University of Minnesota, Minneapolis, Minnesota

ABSTRACT

Part I of this study starts with a review of some common errors in petrologic calculations. The sources and accuracy of data are referred to and some rules are given for keeping track of the probable accuracy of calculated results. In Part II twenty-six problems are outlined or referred to as illustrations. These are selected to cover a variety of petrologic topics and a variety of methods for handling more or less inaccurate data.

Emphasis is probably to be placed on two points: (1) the fact that calculations cannot give reliable results if based on inaccurate data or unjustified assumptions, but if the amount of error can be estimated, the limits between which the true values lie may be of value even if there is a large range of values between the limits; and (2) where a strict calculation can hardly be applied, there is a method of particular value to petrologists, a method known to mathematicians as "successive approximations."

Part III of the study applies the methods to some calculations in igneous differentiation.

PART I. GENERAL DISCUSSION

INTRODUCTION

The data of geology are less exact than those in many of the other branches of science, and rigorous mathematical treatments of the data are not abundant. The data are improving, however, and the National Research Council has two committees on data, one securing quantitative data, and another obtaining data from commercial examinations and explorations. It is perhaps timely, therefore, to note in a geological journal the rules for calculations based on data, more or less exact, giving examples of good usage as well as calling attention to numerous pitfalls and common errors. Let me be the first to plead guilty of not always following the rules. It is too much to hope that even this discussion of errors is wholly free from errors in its illustrations.

Naturally, since this is not the advocate of any particular form of petrographic calculation, some of the elaborate systems of calculation, which are well stated in the literature, are referred to here in very brief form. Holmes has done a service in compiling within the

covers of one book[1] illustrations of a variety of petrographic calculations. Leith and Mead have also an extensive compilation of methods of calculation in metamorphic geology.[2]

It is a pleasure here to acknowledge having received many suggestions and much constructive criticism of this study from other teachers of petrology. Dr. Arthur Holmes, Dr. Albert Johannsen, Dr. A. N. Winchell, and my colleagues at Minnesota, after long experience with student calculations, have added materially to the value of the discussion. In a small way, therefore, it approaches the record of a symposium on the subject.

COMMON ERRORS

This section is intended not as a destructive criticism merely. It is an attempt to suggest the methods of avoiding errors, and it seems that in a few cases the simple statement of the error is almost enough to show the method of correction.

1. *Neglect of proof of work.*—Before publishing revolutionary ideas based on calculations, the student should check his work, repeat the calculation, and preferably also have it checked by another individual. The summation of a column of figures should never be neglected. An adding machine is often of value.

2. *Errors in the units considered.*—Even geologists of long experience and generally careful work find that errors creep into the units or data transferred.

3. *Neglect of a check on consistency of two sets of data.*—Many rocks have been described in terms of both minerals and chemical constituents. If one is calculated from the other there may be a disagreement. For example, soda[3] or magnesia[4] may be shown in amounts not indicated by minerals.

[1] Arthur Holmes, *Petrographic Methods and Calculations* (London: Murby and Co., 1921).

[2] C. K. Leith and W. J. Mead, *Metamorphic Geology*, Part IV, "Laboratory Work." Henry Holt and Co., 1915.

[3] F. F. Grout, "The Vermilion Batholith of Minnesota," *Journal of Geology*, Vol. XXXIII (1925), p. 471.

[4] Carl Zapffe, "Effects of a Basic Igneous Intrusion," *Economic Geology*, Vol. VII (1912), pp. 149–75.

Larsen[1] notes also that optical data for many minerals are inconsistent.

4. *Confusion in the relation of weight, volume, and specific gravity, especially that of mixtures or porous material.*—Sharwood has discussed two different examples of this error in sufficient detail,[2] giving correct formulas for estimating specific gravity. See also Problem 13.

Rocks are described as light or dark, largely on the basis of the volume of the constituents, but the usage is not universally understood—the student might decide that dark minerals predominate if the norm, which is based on weight percentages, shows over 50 per cent femic minerals. In any case it is best to state which is meant.

Calculations of analyses by weight should not be based on Rosiwal measurements of volume without correction. The same relation applies in the calculation of the composition of a differentiated mass after the volumes have been measured.[3] The correct procedure is to multiply the proportions by volume by the respective gravities, yielding proportions by weight. The latter can be reduced to percentages by weight and these used in calculating the compositions of mixtures or averages.

There are also, of course, simple mistakes in statement which may not imply a fundamental confusion of volume and weight.[4]

5. *Assumption of some constant, either volume, weight, or constituent, in case of rock alteration.*—When a limestone at the contact of an igneous rock is altered to amphibolite and the analyses are as in the following table,[5] it is wholly uncertain that 39.2 per cent of lime

[1] E. S. Larsen, "Microscopic Determination of Non-Opaque Minerals," *U.S. Geol. Survey Bulletin 679* (1921), p. 10.

[2] W. J. Sharwood, "The Specific Gravity of Mixtures," *Economic Geology*, Vol. VII (1912), pp. 588–90.

[3] L. V. Pirsson, "Igneous Rocks of the Highwood Mountains," *U.S. Geol. Survey Bulletin 237* (1905), pp. 180–93; A. P. Coleman, "The Nickel Industry," *Monograph, Canada Department of Mines* (1913), pp. 106–7; G. W. Tyrrell, "The Picrite-Teschenite Sill of Lugar," *Quarterly Journal Geological Society*, Vol. LXXII (1916), pp. 118–21. The corrections for specific gravity are ignored, but may possibly be negligible errors in comparison with the error in the volumes, which are known to be rough estimates.

[4] See, for example, Bain's reference to volume where weight was used, in "Assimilation by the Sudbury Norite Sheet," *Journal of Geology*, Vol. XXXIII (1925), p. 515.

[5] W. G. Foye, "Nephelite Syenites of Ontario," *American Journal of Science*, Vol. XL (1915), p. 431.

has been lost or 47.7 per cent of silica added, as claimed by the author discussing the case.

	Amphibolite	Limestone
SiO_2	50.00	2.27
Al_2O_3	18.84	....
Fe_2O_3	2.57	1.31
FeO	5.51	....
MgO	4.63	3.20
CaO	10.65	49.88
Na_2O	4.48	....
K_2O	1.18	....
CO_2	0.10	42.73
Others	2.03	....
	99.97	99.39

6. *Neglect of all data.*—It is not rare for petrologists, even those of long experience, to ignore all data and base sweeping conclusions on qualitative ideas. The effects of viscosity in magmas are thus variously estimated:

Harker thought diffusion[1] had important effects in magmas, but that magmas are too viscous to allow much crystal settling.[2] Daly approved the idea of crystal settling in magmas,[3] but indicates that the magma is too viscous for diffusion or much deep-seated convection.[4] Pirsson thought convection occurred in a laccolith,[5] but considered diffusion unimportant in such a viscous liquid.[6] Thus we get around a circle, and all the processes mentioned deserve consideration quantitatively. Fortunately Bowen has supplied some laboratory data[7] and others have supplied a sufficiently close check by field observations,[8] so that we now feel confident that diffusion is

[1] A. Harker, *The Natural History of Igneous Rocks* (New York: Macmillan Co., 1909), pp. 223, 319.

[2] *Op. cit.*, pp. 319–22.

[3] R. A. Daly, *Igneous Rocks and Their Origin* (McGraw-Hill Book Co., 1914), pp. 22–27.

[4] *Op. cit.*, pp. 222 and 224.

[5] L. V. Pirsson, "Igneous Rocks of the Highwood Mountains," *U.S. Geol. Survey Bulletin 237* (1905), pp. 187–88.

[6] *Op. cit.*, p. 184.

[7] N. L. Bowen, "Crystallization Differentiation in Silicate Melts," *American Journal of Science*, Vol. XXXIX (1915), p. 186.

[8] G. F. Becker, "Some Queries on Rock Differentiation," *American Journal of Science*, Vol. III (1897), p. 29; R. A. Daly, "Mechanics of Igneous Intrustion, *American Journal of Science*, Vol. XXVI (1908), p. 30.

extremely slow, while crystal-settling and convection are still worthy of consideration.

7. *Assuming that a calculation gives an exactness not found in observation.*—There are many examples. Perhaps the most prominent petrographic example is the CIPW system of igneous rock classification by a calculation of norms, proposed in 1902 with great emphasis on the fact that it brought together rocks of similar chemical composition and was established on a strictly quantitative basis.[1] It remained for Mathews in 1918 to show by statistics, calculations, and tables that commensurate groups in the mode classification are about as well characterized chemically as those in the norm classification.[2] The advantages of the CIPW system as a quantitative system appear chiefly in the facility with which one can divide and characterize chemical units of smaller size than those commonly distinguished in the mode system.

7*a*. *Assuming that an average value for a variable group of things gives the things a uniformity.*—The average of a few analyses of the basal part of an intrusive is hardly any better indication of the nature of the intruded magma than one particular analysis in the series. If such a series showed very slight differences and there were confirmatory field evidences of uniformity, early solidification, etc., the average might be considered safe as a basis of calculation. On the other hand, when the analyses show wide variation and the field observations show bands and basal segregations, and the intrusive is so enormous as to prevent a rapid chilling, the average analysis should be considered almost useless for calculation.[3] There are many such examples.[4]

8. *Making too great an extrapolation, or using a formula beyond the proper range of its application.*—The dangers of long-range esti-

[1] W. Cross, J. P. Iddings, L. V. Pirsson, and H. S. Washington, *Quantitative Classification of Igneous Rocks* (University of Chicago Press, 1903), p. 234.

[2] E. B. Mathews, "Relative Efficiency of Normative and Modal Classifications of Igneous Rocks," *Bulletin Geological Society of America*, Vol. XXX (1919), p. 92.

[3] G. W. Bain, "Assimilation by the Sudbury Norite Sheet," *Journal of Geology*, Vol. XXXIII (1925), pp. 509–25.

[4] R. A. Daly, *Igneous Rocks and Their Origin* (McGraw-Hill Book Co., 1914), p. 315, seems to assume a uniform primitive basalt. H. S. Washington, "Deccan Traps and Other Plateau Basalts," *Bulletin Geological Society of America*, Vol. XXXIII (1912), pp. 765–804, shows the variability of the great basalts of lava fields.

mates are apparent from the several attempts to extrapolate the change of fusion temperature with pressure. Barus extrapolated a straight line from experiments indicating a rise of 1° C. from an increase of 40 atmospheres pressure.[1] Tamman suggested that the temperature would first rise and later decline. Bridgman's work is most thorough and shows that as far as volume is concerned, the change with pressure diminishes at high pressures, but shows no sign of vanishing.[2] Figure 1 shows the several attempts at extrapolation. They are all guesses, but the central parabolic curve is in best accord with the data of experiments, is intermediate between the other estimates, and may well be favored.

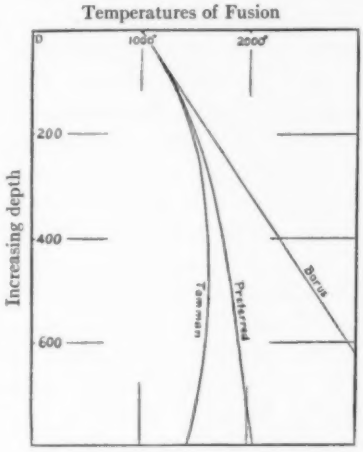

FIG. 1.—Diagrammatic contrast in the several extrapolations of the fusion-depth curves.

9. *Assuming that an assumption is correct, or neglect of multiple working hypotheses.*—It is perfectly proper to base calculations on a reasonable set of data and a hypothesis as to a process. The deductive method in science is to make an assumption and test it by showing its consequences either by calculation or otherwise. The simple fact, however, that some calculation gives reasonable results, does not prove that the original hypothesis or assumption was correct; several other hypotheses might give equally good results, and there is no rigorous logic in favoring one more than another.

For example, near the border of a granite some hornblendite masses are assumed to be altered limestone, and a calculation shows

[1] C. Barus, "Igneous Fusion and Ebullition," *U.S. Geol. Survey Bulletin 103* (1893), p. 55.

[2] See summary by John Johnston, "Recent High Pressure Investigation," *Journal Franklin Institute* (January, 1917), pp. 7–12; and J. Barrell, "The Spheres of Earth," *American Journal of Science*, Vol. X (1925), p. 508.

that the hornblendite has about the composition of a mixture in proper amounts of the original limestone with the granite magma. The satisfactory check afforded by the calculation, however, in no way affects the evidence found elsewhere that many hornblendite masses form by differentiation of a granite magma where the walls are not limey or hornblendic. The two theories need further evidence before a choice is possible between them.

In many cases, however, the petrologist who invents and tests such a theory develops an affection for his intellectual offspring and elevates it to the rank of a "ruling theory." Dr. T. C. Chamberlin long ago called attention to this early error,[1] which has unfortunately not entirely passed away with the infancy of investigation.

A recent paper on the assimilation that may have occurred in the Sudbury norite magma[2] closes with results stated in terms of "minimum possible amount" of assimilation, tacitly ignoring all other theories and hypotheses offered to explain rock variation. The same paper also assumes, without convincing evidence, that the basal phase of the intrusive is "average magma," disregarding all theories of crystal settling, immiscible separation, or heterogeneous intrusion, any one of which might reverse the result of the calculation based on that "average magma."

Even those petrologists who use multiple working hypotheses should be careful to be provided with a long list of ideas.[3]

10. *Neglect of probable errors in data and calculation.*—For various reasons it is impossible to obtain the absolute value of an unknown quantity, unless it is perhaps the count of the number of certain objects. Any measurement is affected to a greater or less extent by errors, which may be classified as constant and accidental, or as regular and erratic.

There are errors arising from the change of length of scale with temperature; instrumental errors, from a faulty adjustment of ap-

[1] T. C. Chamberlin, "The Method of Multiple Working Hypotheses," *Journal of Geology*, Vol. V (1897), pp. 837–48.

[2] G. W. Bain, *op. cit.*

[3] W. A. Richardson, "The Frequency-Distribution of Igneous Rocks," *Mineralogical Magazine*, Vol. XX (1923), pp. 1–19. The author tests four theories as to the diversity of igneous rocks, but ignores the relation of rock to *form of occurrence.*

paratus; personal errors; blunders. These may be largely eliminated by prolonged and detailed work.

"Intrinsic errors" may be illustrated by the estimate of a banded differentiate by analyses of some bands.[1] Such an estimate is likely to be as full of error as the measurement of the length of a live angleworm! (See also paragraph 7*a*.) The best that can be done in such cases is to determine the probable limits within which the result lies.

10*a*. *Assuming that data from physics, chemistry, etc., are exact and 100 per cent perfect.*—Lord Kelvin's calculation of the age of the earth, using physical data and some assumptions, now discarded, dominated geologic thought many years, and it is all too common also for petrologists to accept a chemist's report as if the figures given were exact to two decimal places, as commonly reported.

10*b*. *Poor selection of data.*—If all the data reported are equally exact, they may be equally good as a basis of calculation. Data, however, are rarely so uniformly good, and those values known to be liable to greatest error should be avoided. A recent paper[2] bases a long and complex series of calculations on the magnesia and alumina contents of a rock, the magnesia making up only about 5 per cent of the whole, while the more accurate estimate of silica is almost ignored.

11. *Confusion of the work by unnecessarily complex methods.*—Many men have devised methods of comparing analyses and calculating the results of mixing rocks. A recent paper gives a false appearance of exactness[3] by using lengthy rigorous methods, though having inaccurate data to start with. A simpler method is given in Problem 26 as an example of "successive approximations," a problem in assimilation.

SOURCES OF DATA

In the writer's experience with student assignments the most useful compilations and sources of further references are F. W. Clarke's "Data of Geochemistry" in the several editions as a bulletin, and H. S. Washington's "Analyses of Igneous Rocks, 1884–1913," as *Professional Paper 99*, both of the United States Geological Survey;

[1] G. W. Bain, *op. cit.* [2] *Ibid.* [3] *Ibid.*

R. A. Daly's *Igneous Rocks and Their Origin;* and Boeke and Eitel's *Grundlage der physikalisch-chemischen Petrographie.* Many others may be more important in special cases.[1]

Each new problem may require data from some new and unsuspected source, so that a complete compilation is hardly to be expected. The necessary information should be sought first by reference to bibliographies, of which *Bulletins 746* and *747* of the U.S. Geological Survey are most useful. The ten-year indexes of *Chemical Abstracts* and the *Treatise on Sedimentation* also contain much petrologic data. Some manuscript bibliographies have been listed by the National Research Council. Finally, new data are added by the student himself as a result of observation, analysis, calculation, etc.

ACCURACY OF DATA

The several compilations and scattered data exhibit different methods of showing the degree of accuracy of the data recorded. All too often there is no guide at all as to the probable error. Students should invite the mature judgment of some one familiar with inaccurate data before basing any radical conclusions on calculations.

The first and most approved method is that of showing the probable error by a figure following the value recorded. If the accuracy of the last figure is probably within two units, this is expressed by writing, for example, 2.54 ± 2, meaning that the true value lies between $2.54 + .02$ and $2.54 - .02$.

A second method often used for less accurate data is to state the limits between which the true value probably lies.

A third method is commonly used in stating large numerical results. If several million units are involved, the thousands units

[1] C. R. Van Hise, "A Treatise on Metamorphism" *U.S. Geol. Survey Monograph 47*, 1904; J. H. L. Vogt, "The Physical Chemistry of the Crystallization and Magmatic Differentiation of Igneous Rocks," *Journal of Geology*, Vols. XXIX, XXX, XXXI, 1921, 1922, 1923.

For geothermal data, see R. A. Daly, "The Earth's Crust and Its Stability," *American Journal of Science*, Vol. V (1923), p. 352; for sedimentary, see H. C. Sorby, *Quarterly Journal Geological Society*, Vol. LXIV (1908), p. 172; for volcanic gases, see E. T. Allen, *Journal Franklin Institute*, Vol. CXCIII (1922), pp. 29–80; for water, see *U.S. Geol. Survey Water Supply Papers 364* and *560C;* for meteorites, see compilations by Farrington, discussed in *U.S. Geol. Survey Prof. Papers 127* and *132;* for atomic weights, see *Journal American Chemical Society*, Vol. XLVII (1925), p. 600.

may be so uncertain as to be best written as ciphers (or 10^n). In this case the significant figures before the ciphers (or 10^n) are taken as indicative of the degree of accuracy. It is somewhat customary to record before the ciphers one more significant figure than is certain to be correct. The probable error thus affects only the last significant figure. Unfortunately this custom or conventional method is not adhered to as universally as is desired.

Finally, some values may be stated in exact figures with a remark that they are "probably of the right order of magnitude." If a value 14×10^8 is of the right order of magnitude, the true value is probably closer to 14×10^8 than to 14×10^7 or 14×10^9. This range should be taken as an extreme, and the expression commonly indicates values that are approximations much closer than that.

Many data, for convenience, are plotted, and the graph gives readings as a basis for calculation. The abscissas and ordinates of a plotted curve cannot be laid down with greater accuracy than about $\pm.02$ inch. In a diagram 4 inches long, then, the percentage error is about .5 per cent at least.

The special case of chemical data.—Chemists commonly report all determinations to two decimal places without notation of the probable error. This is for convenience and uniformity, and shows the limit of accuracy of weighing rather than of manipulation. Furthermore, the chemists understand, from the discussions of Washington[1] and of Hillebrand,[2] about how much error to expect in good work on the common constituents of rocks.

Probably the allowable error in the major constituents may reasonably be expected to be less than .3 per cent of the rock. For constituents that make up 1 per cent to 10 per cent of the rock, the error should not be more than .03 per cent to .10 per cent of the rock. It is noteworthy that although the error in minor constituents is a smaller percentage of the rock, it is a larger percentage of the total amount of the constituent determined.

If there are evidences of careless work, errors may be much

[1] H. S. Washington, *The Chemical Analyses of Rocks* (3d ed., Wiley and Sons, 1919), pp. 125–29.

[2] W. F. Hillebrand, "The Analysis of Silicate and Carbonate Rocks," *U.S. Geol. Survey Bulletin 700*, pp. 30–31.

larger. Two constituents are especially likely to serious error, viz., magnesia and alumina. Washington[1] shows that in several cases these oxides are in error as much as 3 per cent of the rock. Robinson also shows evidence of the generality of this error in magnesia.[2] Many analysts also have neglected the distinction between ferrous and ferric oxides.

The criteria for judging the quality of analyses are given by Washington:[3] agreement with the mode, summation near 100 per cent, methods used in analysis, and a comparison with analyses of similar and related rocks. By such criteria Washington has classified the thousands of published analyses of igneous rocks into five grades, and concludes that only the first- and second-rate analyses should be countenanced by petrographers, though some third-rate work may serve special purposes. Fourth- or fifth-rate analyses are of little use in petrology.

SOME RULES FOR CALCULATION

A considerable literature has developed in discussion of the methods of keeping track of the approximate accuracy through a more or less complex calculation.[4]

Error in a single reading.—Measurements on a scale are usually read to the small divisions on the scale and estimated to the tenth of a small division.

Rule 1: *The estimate is likely to be correct within one-tenth of the small division on the scale.* If a reading is 3.27 cm. and the scale is divided into millimeters, the last significant figure in the reading is estimated and it may be assumed to be within .01 cm. of the correct value.

Error in average.—If several readings are taken of the same quantity they will differ among themselves because of the estimated

[1] H. S. Washington, "Chemical Analyses of Igneous Rocks," *U.S. Geol. Survey Prof. Paper 99* (1917), pp. 15, 20.

[2] H. H. Robinson, "Summation of Chemical Analyses," *American Journal of Science*, Vol. XL (1916), p. 260.

[3] *U.S. Geol. Survey Prof. Paper 99*, pp. 18–26.

[4] See, for examples, W. S. Franklin, *Precision of Measurement* (Lancaster, Pa.: Franklin & Charles); and Zeleny and Erikson, *A Manual for Physical Measurements* (4th ed., McGraw-Hill Book Co., 1919).

parts, and because one cannot each time obtain the same conditions or the same adjustment of apparatus. Simple formulas are in use for the probable error in the average of such readings.

Rule 2: *The probable error,*

$$E = \pm \frac{0.85}{n\sqrt{n-1}} \Sigma V ,$$

where n is the number of readings averaged, and ΣV is the sum of all the differences (regardless of sign) between the readings and the arithmetical mean. For example:

Let the readings be	2.53	Then V is for each	.018
	2.56		.012
	2.55		.002
	2.56		.012
	2.54		.008
Then the mean is	2.548	and ΣV is	.052

The probable numerical error is

$$E = \frac{.85}{5\sqrt{5-1}} .052 = .004 ,$$

and the result is written 2.548 ± 4. The figures to the right of the one affected by the error are of no value and are normally omitted, though in some cases the mean is carried to two figures beyond the certain value, and the probable error is stated in two significant figures.

The probable percentage error in this example is .17 per cent, and the result may be written $2.548 \pm .17$ per cent.

Error in computed results.—

Rule 3: *In addition or subtraction, retain in the sum or difference the largest numerical error in the quantities involved.*

Rule 4: *In multiplication or division, retain in the product or quotient the percentage error of the least accurate data involved.*

Rule 5: *When raising a quantity to any power, multiply the percentage error in the quantity by the exponent.*

Negligible errors.—When a result is to be calculated from several quantities it often happens that some data have probable errors so

large that the errors in other factors are negligible. Some quantities to be used in calculation ought to be determined with the greatest possible precision, while accurate work on others, beyond a certain easily attained accuracy, is wasted effort.

Rule 4, given previously, suggests that any smaller percentage error than the percentage error in some other factor would not affect the result.

Rule 6: A stricter mathematical treatment of the problem[1] indicates that the *percentage error in measurement of one factor is negligible if less than .46 of the percentage error in the other factor.*

PART II. METHODS AND EXAMPLES

It is hoped that the examples here selected will illustrate a variety of methods and be suggestive to students. The references are chiefly those of easy access, and where the reference includes a good example, the details are here omitted. The classification of methods is tentative and may not be approved by experts in mathematics or statistics, but serves to subdivide, for purposes of discussion, a group that is essentially miscellaneous. Possibly emphasis should be placed on certain little used but very useful methods such as that of successive approximations: Problems 26, 27, and 28.

SIMPLE STATISTICAL METHODS

Problem 1.—A measurement of a thin section by the Rosiwal method or some modified scheme[2] is essentially statistical. Its accuracy has been reported satisfactory for many purposes,[3] and a convenient form of recording results is shown by Pirsson.[4]

Here may be included also such statistical methods as the microscopic work on powdered ore,[5] the estimation of areas for the several rock families,[6] and the studies of fracturing in the minerals of the Sudbury norite sheet.[7]

[1] Franklin, *op. cit.*, p. 9. [2] See under graphical methods, etc., below.

[3] A. Johannsen and E. A. Stephenson, "On the Accuracy of the Rosiwal Method," *Journal of Geology*, Vol. XXVII (1919), pp. 212.

[4] *U.S. Geol. Survey Bulletin 237*, p. 73.

[5] W. H. Coghill and J. P. Bonardi, "Approximate Quantitative Microscopy of Pulverized Ores," *U.S. Bureau of Mines, Technical Paper 211*, 1919.

[6] R. A. Daly, "Igneous Rocks and Their Origin," pp. 42–52.

[7] Myron Dresser, "Some Quantitative Measurements of Minerals of the Nickel-Eruptive at Sudbury," *Economic Geology*, Vol. XII (1917), No. 7, pp. 563–80.

ESTABLISHMENT OF ACCURATE VALUES FROM A SET OF STATISTICS

Problem 2.—To take an average of a series of readings. The probable error in the mean is

$$E=\frac{.85\Sigma v}{n(\sqrt{n-1})}.$$

This value depends so largely on n, the number of readings, that no less than five or ten readings should be considered essential to a fair average.

Problem 3.—A more complicated average is that based on several analyses, by different chemists, of the rock in some igneous masses, such as a lava flow which may be assumed to be uniform. The calculation of each constituent is an independent problem involving a probable error determined by the same formula as the preceding.

THE AVERAGE NATURE OF A VARIABLE GROUP OF MATERIALS

Problem 4.—To estimate the nature of average igneous rock, or or average diorite. The data are incomplete as to the volumes and compositions involved. It is not uncommon to assume that an average of *analyses*, selected or all-inclusive, will be a close approximation to the desired average, but the errors may be large. Two methods of averaging are in use: the sum of the percentages of a constituent may be divided either by the total number of analyses or by the number of analyses in which that constituent was determined.[1]

TAKING A MAXIMUM VALUE FROM A SET OF READINGS

Problem 5.—As a petrographic problem, what is the maximum symmetrical extinction of adjacent twinning bands in the plagioclase of a certain igneous rock? It may safely be said that at least as many random grains should be tested as for a safe average. The texts call for four readings,[2] but, judging by experience with many classes, ten would be safer. In many such problems certain features may modify the procedure, but the beginner should not be satisfied with a small number of readings.

[1] F. W. Clarke and H. S. Washington, "The Composition of the Earth's Crust," *U.S. Geol. Survey Prof. Paper 127* (1924), p. 11.

[2] LuQuer, *Minerals in Rock Sections*, 1898 ed., p. 76. Later editions say "as many as possible." Weinschenk (Clarke) says "a large number." Iddings, *Rock Minerals*, p. 225, says "as many as possible."

CORRELATION OF TWO KINDS OF STATISTICAL DATA

Problem 6.—What is the relation of the silica content of natural glasses to their indices of refraction?[1] The method consists in the compilation of all the data and plotting the two sets on co-ordinate paper, using one set of values as abscissas and the other as ordinates. If proper statements are added as to the divergence of the curve from

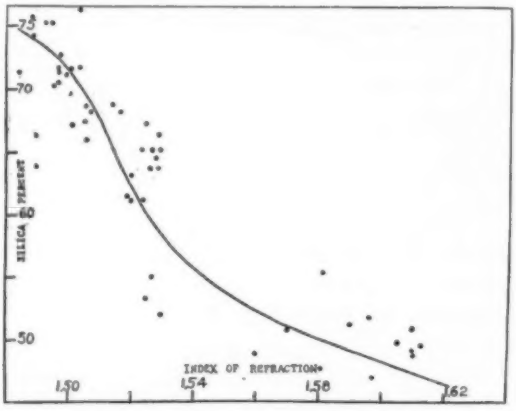

FIG. 2.—The correlation of indices of refraction and silica content in natural glasses. After George.

the correct value, as was done in a paper by George, the curves serve a very useful purpose (Fig. 2).

Numerical correlation in a rough way can be made also. For example, in the case of glasses, the indices of refraction of all the specimens in certain restricted groups based on composition can be averaged.

A study of a very different sort is that by H. S. Washington, of the correlation of rock densities and elevations.[2]

[1] Michael Stark, "Zusammenhang des Brechungsexponenten natürlicher Gläser mit ihren Chemismus," *Min. u. Pet. Mitt.*, Vol. XXIII (1904), p. 536; W. O. George, "The Relation of the Physical Properties of Natural Glasses to Their Chemical Composition," *Journal of Geology*, Vol. XXXII (1924), pp. 353–72; C. E. Tilley, "Relations of Some Natural Glasses," *Mineralogical Magazine*, Vol. XIX (1922), pp. 275–94.

[2] H. S. Washington, "The Chemistry of the Earth's Crust," *Journal of Franklin Institute*, Vol. CXC (1920), pp. 804–14.

A still different sort is the correlation of rounding of pebbles and distances of transportation.[1]

INTERPOLATION AND EXTRAPOLATION

Problem 7.—In 1896 a few members of the olivine group were tested and a curve drawn to indicate the properties of the series.[2] This curve between determined points is an interpolation (Fig. 3). It has been amply justified by later tests on olivine with compositions intermediate between those shown on the curve.

Problem 8.—Many petrographers use tables in calculating the norms of igneous rocks. If the tables are carried only to the first decimal, the student may find intermediate values by interpolation.

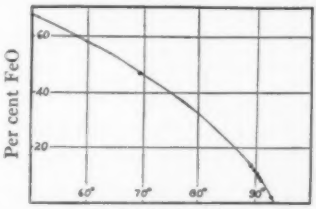

FIG. 3.—The curve showing, by interpolation, the relation of optic angle and per cent of FeO in olivines. After Penfield and Forbes.

Problem 9.—Washington found it very suggestive to plot a series of curves showing the differentiation of the rocks at Magnet Cove, Arkansas, and extrapolate the curves at both ends to see what might be expected as next in the series.[3] Robinson has done much the same at the San Franciscan volcanic field.[4] The possibility of actual differentiation, however, of the kind indicated by the curves is not certain.

SIMPLE CALCULATIONS FROM KNOWN AND ESTIMATED DATA AND FORMULAS

Hundreds of papers and textbooks develop arguments by the use of simple formulas and the available data. The selections here made are by no means to be considered as comprehensive. The problems

[1] C. K. Wentworth, "Measuring and Plotting the Shapes of Pebbles," *U.S. Geol. Survey Bulletin 730C.*

[2] Penfield and Forbes, "Optical Properties of the Chrysolite-Fayalite Group," *American Journal of Science*, Vol. I (1896), p. 134.

[3] H. S. Washington, "Foyaite-Ijolite Series of Magnet Cove," *Journal of Geology*, Vol. IX (1901), pp. 651–56.

[4] H. H. Robinson, *U.S. Geol. Survey Prof. Paper 76* (1913), pp. 180–203.

in metamorphism given by Leith and Mead, though full of petrologic interest, are not quoted here. A slight modification of this method is the use of graphic methods instead of a formula.[1]

SPECIFIC GRAVITIES OF MIXTURES

Problem 10.—Given the specific gravities of the minerals of a rock and their proportions by weight or by volume, what is the specific gravity of the rock? The specific gravity of a rock, assuming its substance to be non-porous, may be calculated by the formula:[2]

$$D=\frac{v'd'+v''d''+v'''d'''\ldots.}{100} \quad \text{or}$$

$$D=\frac{100}{\frac{w'}{d'}+\frac{w''}{d''}+\frac{w'''}{d'''}\ldots.}$$

where D is the required aggregate specific gravity; v', v'', v''', etc. are the volume percentages of constituents I, II, III, etc.; w', w'', w''', etc. are the weight percentages; and d', d'', d''', etc. are the specific gravities of the same series of constituents.

Some have also used the specific gravities calculated from normative minerals, instead of from the mode.[3]

VOLUME CHANGE IN METAMORPHISM

Problem 11.—Given two molecules of $CaCO_3$, replaced by one molecule of $CaMg(CO_3)_2$, what is the volume change? Van Hise stated the rule[4] and made numerous calculations of that sort. Barrell has shown that while some reactions involving hydration result in expansion when the water is added and CO_2 escapes, the same re-

[1] Leith and Mead use such a method for the ratio of sand, limestone, and shale that may be formed from an igneous rock. Anderson and Bowen give a curve of the melting behavior of binary mixtures of MgO and SiO_2, in *Zeit. f. anorg. Chem.*, Vol. LXXXVII (1914), p. 283, from which one can estimate how much free silica could result from crystal settling in an olivine rock.

[2] W. J. Sharwood, "The Specific Gravity of Mixtures," *Economic Geology*, Vol. VII (1912), pp. 588–90.

[3] J. P. Iddings, "Densities of Igneous Rocks Calculated from Their Norms," *American Journal of Science*, Vol. XLIX (1920), pp. 363–66. See also Washington's estimates of specific gravity in *Journal Franklin Institute*, Vol. CXC (1920), pp. 804–6.

[4] C. R. Van Hise, "A Treatise on Metamorphism," *U.S. Geol. Survey Monograph 47*, p. 209.

actions result in a large shrinkage if the volumes of both these constituents are included before and after reaction.[1]

The complex reaction for the formation of grossularite is calculated to volumes by Barrell,[2] who gives the method in clear outline.

THE COMPOSITION OF THE AVERAGE ROCK IN A DIFFERENTIATED OR VARIABLE MASS

This is sometimes erroneously called the original magma.

Problem 12.—Given the volume of each phase (or dimensions from which to estimate volume) and the specific gravity and the analysis of each, what is the mean composition of the whole mass? The calculation has been outlined for a mass from Magnet Cove, Arkansas,[3] and for one from Norway.[4] The accuracy varies with the care used in estimating volumes and in sampling the fractions, as well as with the quality of the analyses.

RATE OF SETTLING OF SOLIDS IN MAGMAS

Problem 13.—How fast should crystals of olivine settle in a melt of olivine? The formula for the rate of settling spheres given by Stokes has limited application,[5] but the range of its applicability as discussed by Allen[6] probably includes this case.

$$x = \frac{2gR^2(d - d_1)}{9V}$$

where x is the rate in centimeters per second, R is the radius in centimeters, d is the density of solid, d_1 is the density of the liquid around it, g is the acceleration of gravity, and V is the viscosity.

Let the viscosity be assumed to be 5, from Bowen's estimate for basic magmas. Let the crystal have a radius of .1 cm., as in common

[1] Joseph Barrell, "Relation of Subjacent Igneous Invasion to Regional Metamorphism," *American Journal of Science*, Vol. I (1921), pp. 179–80.

[2] J. Barrell, "Physical Effects of Contact Metamorphism," *American Journal of Science*, Vol. XIII (1902), pp. 289–90.

[3] H. S. Washington, "Foyaite-Ijolite Series of Magnet Cove," *Journal of Geology*, Vol. IX (1901), pp. 657–63. Washington used two methods of estimating volumes.

[4] Steinar Foslie, "Field Observations in Northern Norway," *Journal of Geology*, Vol. XXIX (1921), pp. 709–12.

[5] *Transactions of the Cambridge Phil. Society*, Vol. IX (1850), No. 2, p. 8.

[6] *Phil. Magazine*, Vol. L (1900), p. 324.

rocks. Then if the difference in density is .19, as an approximate mean of estimates by various investigators, the formula becomes:

$$x=\frac{2\times 980\times .01\times .19}{9\times 5}=0.083 \text{ cm. per second,}$$

or nearly 5 centimeters every minute. With all allowance for errors in the data, it is likely that the rate is between 2 and 10 cm. per minute.

DEPTH OF "COMPENSATION"

It is generally agreed, from a multitude of observations, that the igneous rocks exposed in regions of high altitudes are lighter than those exposed in the low plains and ocean basin regions. It is not so generally agreed how these observations are to be interpreted as to conditions underground.[1] Whether or not the differences in density and the larger topographic features are compatible with the notion of fairly uniform "earth shells" of differing materials, and whether these relatively uniform shells reach within a few miles of the surface, are still matters of discussion. The rigorous mathematical treatment of the problem involves more factors than can be considered here, but a short problem may serve to show the order of magnitude of depths that must be considered.

Problem 14.—If differences in specific gravity of igneous rocks on continents and ocean basins are characteristic, how deep must the rock columns extend before they rest on the rock below with equal pressures?

The data are estimated in several ways, perhaps best by Washington,[2] who gives an elaborate calculation.

North America: density = 2.75; elevation = +1,888 feet
Pacific floor: density = 2.89; elevation = −14,820 feet

A first correction is to be made for the 14,820 feet of water resting on the Pacific floor. This, at a density of 1.027 (Clarke), is equivalent to some 5,266 feet of rock with a density of 2.89. This leaves

[1] William Bowie, "The Airy, or 'Roots of Mountains,' Theory," *Science*, Vol. LXIII (1926), p. 371.

[2] H. S. Washington, "Chemistry of the Earth's Crust," *Journal Franklin Institute*, Vol. CXC (1920), p. 801; "Isostasy and Rock Density," *Bulletin Geological Society of America*, Vol. XXXIII (1922), pp. 375–410.

14,820 − 5,266 = 9,544 feet below sea-level as the basis of calculation for the Pacific floor.

Let x = the number of feet below sea level where the pressures are equal. Then

$$\begin{aligned}(x-9{,}544)2.89&=(x+1{,}888)2.75\\ 2.89x-27{,}611&=2.75x+5{,}192\\ .14x&=32{,}803\\ x&=\text{a little over } 234{,}000\end{aligned}$$

The rock columns in such a hypothetical case would extend to a depth of 40 miles.

It is now time to test the assumptions involved in the original statement of the problem. The average rock for North America is a quartz-bearing rock somewhat resembling quartz monzonite, and a calculation of the products of differentiation, in percentages of the silicate "shell" of earth (Problem 27, following), indicates that there is probably not enough potash in the earth to permit a "continental mass" of monzonite 40 miles thick. It seems likely that acid surface rocks change somewhat gradually to basic rocks in depth. If we assume that the difference in density at the surface, 2.89 − 2.75, fades out in depth to a more uniform basaltic or peridotitic zone near the depth of compensation, then that depth must be considerably greater than 40 miles; perhaps twice as great.

METEORITES AND THE EARTH'S INTERIOR

The nature of the earth's deeper interior has been variously estimated, and the sequence of theories has been recently reviewed by Adams and Williamson,[1] who conclude that "beyond reasonable doubt the earth has a metallic core of iron or nickel-iron." This is not universally accepted, but some calculations are possible as to the relation of this earth to meteorites.

Problem 15.—What is the probable *amount* of metallic earth core, and what is the thickness of stony material?

A method of approach suggested by Clarke and Washington[2] is that of estimating the nature of meteorites by average analyses of

[1] L. H. Adams and E. D. Williamson, "The Composition of the Earth's Interior," *Smithsonian Reports for 1923, Publication 2767* (1925), pp. 241, 260.

[2] F. W. Clarke and H. S. Washington, "The Composition of the Earth's Crust," *U.S. Geol. Survey Prof. Paper 127*, pp. 34–35.

both stone and iron falls, weighting each according to the amounts of each observed. The data, however, are very incomplete.[1]

As an approximation, equal weights of stony and iron material may be used in the calculation of the amount of core and shell. A first correction should be made for the occurrence of some 12 per cent of metals, carbides, etc. in the stony meteorites. If allowance is made for these, the average of all meteorites must be near 58 or 60 per cent by weight of metallic or heavy material. The average specific gravity of stony meteorites, 3.51,[2] and that of iron meteorites, about 7.8, may be increased on account of compression, as estimated by Adams and Williamson, to about 4.0 and 10, respectively. The calculation becomes:

$$\text{weight of core} : \text{weight of outer shell} = 60 : 40$$
$$40 \times \text{weight of core} = 60 \times \text{weight of outer shell}$$

But the weight of a thing is a constant times the product of its volume and specific gravity. Hence (omitting the constant from both sides):

$$40 \times \text{specific gravity of core} \times \text{volume of core}$$
$$= 60 \times \text{specific gravity of shell} \times \text{volume of shell}$$
$$= 60 \times \text{specific gravity of shell} \times (\text{volumes of earth} - \text{volume of core})$$

$$40 \times 10 \times \frac{\pi d^3}{6} = 60 \times 4 \times \left(\frac{\pi D^3}{6} - \frac{\pi d^3}{6} \right)$$
$$d^3 = 3/8 D^3$$
$$d = .72D,$$

with a probable error determined by the original estimate of the weights of meteorites. If D is roughly 7,900 miles, $d = 5{,}688$; and the outer stony material may be approximately 1,100 miles thick, a little over 1,700 kilometers.[3]

[1] Possibly the reason Clarke did not follow up the suggestion. G. P. Merrill, "Handbook of the Meteorite Collections in the U.S. National Museum," *U.S. National Museum Bulletin 94* (1916), p. 27; O. C. Farrington, *Meteorites, Their Structure, Composition and Terrestrial Relations* (1915), p. 4; Harkins, *Journal American Chemical Society*, Vol. XXXIX (1917), p. 864.

[2] Merrill, *American Journal of Science*, Vol. XXVII (1909), pp. 467–74.

[3] This calculation of the thickness of stony material, based on rough estimates of the composition of meteorites, seems to be too low, for a mixture of 60 per cent material with a density of 10, and 40 per cent material with a density of 4, would have a density of 6.25, or more than the earth shows. There should apparently be more stony material than 40 per cent. Clarke notes that several estimates of the thickness of the stony shell range from 817 miles (Daly mentions 325 miles, as based on Farrington's data) to 1,784 miles. Some data or assumptions are evidently erroneous.

ATOMIC AND MOLECULAR PROPORTIONS

One further simple calculation from data leads to the more complex schemes of calculation. This is the problem of atomic proportions, or molecular proportions. A general familiarity with the idea involved serves many purposes, but a number of cases have been found where a student, even after making the elaborate calculations of a norm, had no understanding of the meaning of molecular proportions.

Problem 16.—Suppose a chemist reports the composition of a sulphide as 47 ± 1 per cent Fe and 53 ± 1 per cent S. What is the probable formula of the mineral? The atomic weights are: Fe = 55.84, and S = 32.064. The errors in chemical data are about 2 per cent of the amounts reported, so that the data need not be elaborated farther than to keep three significant figures.

The algebraic rule is to let x be the number of atoms of sulphur for each iron atom. Then

$$\frac{55.8}{32.0x} = \frac{47 \pm 1}{53 \pm 1} \text{ and } x = 1.96 \pm 4 .$$

The arithmetical rule is more generally used: *divide the percentage by the atomic weights, to get the atomic ratios.*

$$\frac{47 \pm 1}{55.8} \text{ atoms of Fe combine with } \frac{53 \pm 1}{32.0} \text{ atoms of S.}$$

$$.84 \text{ atoms of Fe combine with } 1.65 \pm 3 \text{ atoms of S.}$$

The formula should be FeS_2, pending more accurate chemical work.

The next stage in the complexity of such calculations involves the common custom of reporting rock analyses in terms of oxides rather than elements. Instead of determining atomic ratios in a feldspar, for example, one estimates molecular ratios of K_2O, Al_2O_3, SiO_2 etc., as if feldspars were made up of oxides. The fallacy of the idea should not mislead anyone, and the convenience of the method makes it widely used.

Problem 17.—Suppose a feldspar analysis is given in the usual form, stating percentages of oxides; what are the molecular proportions of the oxides in the feldspar? The rule is analogous to the preceding: divide the percentage of each oxide by the molecular

weight of that oxide, and the quotients are proportional to the numbers of molecules present. Since the quotients are commonly decimal fractions, it is customary to multiply each by 1,000 to get whole numbers for discussion, the proportions not being changed by such increase. Tables have been prepared to save the work of calculating (see references, Problem 20 under the later heading, Graphic Methods, etc.).

COMPLEX CALCULATIONS BASED ON DATA, FORMULAS, AND RULES

CALCULATIONS BASED ON MOLECULAR RATIOS

Problem 18.—To find how many constituent molecules enter into an isomorphous mineral.

Given the analyses and molecular ratios of the preceding problem, how many molecules of each component are present, and what percentage of each is present? For convenience the components calculated are the pure chemical compounds, and these are given mineral names, though no one should be misled into thinking that the common specimens of natural minerals consist of a pure compound. Holmes gives the calculation in detail.[1] The three main divisions of the process are: (1) calculation of molecular proportions, as in the preceding problem; (2) assignment of the molecules to simple component minerals; and (3) calculation of the ratio between them; the proportion by weight can also be calculated.

It is noteworthy that not only are the molecular ratios of oxides found in tables, but the last step in the process, that of calculating component minerals from their molecular ratios, is rapidly taken by the use of other tables.[2] Many examples of such calculations are found in the literature.[3]

Problem 19.—To find the molecular ratios of oxides in a rock. Use the same method as outlined for molecular proportions in feldspar. The same tables save one from the detail of arithmetical work.

Problem 20.—To calculate the "standard" minerals (or norm) from an analysis.

[1] *Op. cit.*, pp. 399–403.

[2] H. S. Washington, "Chemical Analyses of Igneous Rocks," *U.S. Geol. Survey Prof. Paper 99*, pp. 1172–80.

[3] See, for example, L. V. Pirsson, "Petrography of Tripyramid Mountain," *American Journal of Science*, Vol. XXXI (1911), p. 417.

The original method (including tables for shortening the arithmetical work) is given by Cross, Iddings, Pirsson, and Washington.[1] This has been only slightly modified after years of experience and is now published in several other places.[2] Blank forms for use in simplifying the calculation have been issued by Berkey and by Holmes.[3] The process is similar in outline to that for finding the ratio of molecules of an isomorphous mixture.

The CIPW classification of igneous rocks is based on data obtained in this calculation.

Problem 21.—To calculate other rock formulas, classifications, or diagrams from analyses.

Osann's method is given in convenient form in the *Fundamental Principles of Petrology*, by Weinschenk (Johannsen).[4] Grubenman's metamorphic rock types are characterized by a similar calculation of ratios.[5] Niggli has a scheme for all rocks, which is also much like Osann's.[6] Hommel uses a different basis for his formulas, but the general process is somewhat similar to Osann's.[7]

Problem 22.—To calculate from an analysis the amounts of the actual minerals known to be present—*the mode*. Kemp gives the method in satisfactory detail with an example.[8] The errors may be large if the rock contains much of a mineral of complex and uncertain composition, such as mica, amphibole, or pyroxene.

[1] *Quantitative Classification of Igneous Rocks* (University of Chicago Press, 1903), pp. 186–204.

[2] *U.S. Geol. Survey Prof. Paper 99*, pp. 1164–80.

[3] Holmes, *Petrographic Methods and Calculations*, pp. 412–32; C. P. Berkey, *Economic Geology*, Vol. VIII (1913), pp. 707–8.

[4] McGraw-Hill Book Company, 1916, pp. 68–71.

[5] U. Grubenman, *Die kristallinen Schiefer* (Berlin: Gebrüder Borntraeger, 1907), Part II, pp. 9–22. A review in English appears in *Journal of Geology*, Vol. XV (1907), pp. 298–301.

[6] *Gesteins- und Mineralprovinzen* (Berlin: Gebrüder Borntraeger, 1923), Band I, pp. 51–60. The method is given in English in *Journal of Geology*, Vol. XXXII (1924), pp. 340–41.

[7] W. Hommel, *Systematische Petrographie auf genetischer Grundlage* (Berlin: Gebrüder Borntraeger, 1919), Vol. I. An English review is given in *Journal of Geology*, Vol. XXX (1922), pp. 484–87.

[8] J. F. Kemp, *Handbook of Rocks* (5th ed., Van Nostrand, 1911), pp. 161–79. Earlier published in the *School of Mines Quarterly*, Vol. XXII (1901), p. 75.

It may be added that the optical characters of minerals, especially if powders are available for a determination of the indices of refraction, help a great deal more in estimating the chemical nature of variable minerals than the kind of rock in which the mineral occurs. There are many good examples of such a calculation.[1] Mead has a blank form for simplifying the calculation.[2]

ESTIMATES OF COMPOSITION

Problem 23.—To calculate the approximate chemical composition of a rock from its Rosiwal measurements or a mineral separation analysis. Holmes gives formulas for calculation, as well as an example.[3] In the literature of petrography there are many examples.[4] The errors, like those in calculating the mode, vary with the care of the Rosiwal measurement, and more especially in the estimates of the composition of micas, amphiboles, pyroxenes, etc. See remarks under Problem 22.

ROCK ALTERATIONS

One of the earliest discussions of rock alteration based on analyses is that by Lindgren[5] on metasomatism; and one of the latest is the same author's study of alteration at Bingham.[6]

The difficulty of knowing exactly what happened in an alteration is shown by Lindgren in two examples,[7] viz., the alteration of pyrargyrite to argentite and the alteration of olivine to serpentine.

The problems become definite only when we know the volume of the secondary substance, or when we know that some constituent remains constant.

[1] Weed and Pirsson, *U.S. Geol. Survey Annual Report*, Vol. XX, Part III, pp. 257 and 466; Robinson, *U.S. Geol. Survey Prof. Paper 76;* Eskola, *Journal of Geology*, Vol. XXX (1922), pp. 269, 275.

[2] W. J. Mead, "Some Geologic Short Cuts," *Economic Geology*, Vol. VII, p. 138.

[3] *Op. cit.*, pp. 392–96.

[4] See, for example, G. W. Tyrrell, "The Picrite-Teschenite Sill of Lugar," *Quarterly Journal Geological Society*, Vol. LXXII (1916), pp. 103, 110.

[5] W. Lindgren, "Metasomatic Processes in Fissure Veins," *Transactions American Institute Mining Engineers*, Vol. XXX (1900), pp. 578–692.

[6] W. Lindgren, "Contact Metamorphism at Bingham, Utah," *Bulletin Geological Society of America*, Vol. XXXV (1924), pp. 507–34.

[7] The first paper cited, pp. 591–92.

CASE 1. THE METHOD OF CONSTANT CONSTITUENT

The method of assuming a constant constituent is used largely in cases of weathering where it can be shown that in many cases alumina is not dissolved appreciably.[1] Leith and Harder have a graphic method also for estimating which constituents probably remained constant in certain cases of alteration. See later section on graphic methods.

Problem 24.—How can the gains and losses in rock alteration be determined when a constituent can be assumed constant? Lindgren gives the method and rules and formulas in sufficient detail.[2] As a whole, however, emphasis should be put on Lindgren's warning that the assumption of a constant constituent should be made only with the greatest caution.

CASE 2. THE METHOD OF CONSTANT VOLUME

The volume of an altered rock is no doubt very often approximately that of the equivalent fresh rock. This has in many cases been assumed from the slender evidence of porosity and texture; it has been strongly argued by Lindgren; and the method is justified by recent accurate studies at Bingham.[3] For accurate work there should be available not only the analyses of fresh and altered rocks, but their specific gravities in powder and in bulk (or a porosity determination with one of these).

Problem 25.—How can the gains and losses in rock alteration be determined when volume remains constant? Calculate first the amounts of each constituent in 100 cc. of fresh rock, and then the same in altered rock. Comparison shows the gains or losses, which may then be transformed into percentage of the original rock, or percentage of the original amount of that constituent present. The method has been applied in a number of districts by Lindgren and by Ransome.[4] The recent Bingham report is a model of careful con-

[1] *Metamorphic Geology*, 1915.

[2] W. Lindgren, *Mineral Deposits* (1913), chap. xx.

[3] W. Lindgren, *op. cit.*

[4] W. Lindgren, *Mineral Deposits* (1913), p. 848; *U.S. Geol. Survey Annual Report*, Vol. XVII (1898), Part III, p. 640, and Vol. XX, Part III, pp. 211–32; *Bulletin Geological Society of America*, Vol. XXXV (1924), pp. 507–34; F. L. Ransome, *U.S. Geol. Survey Prof. Paper 66*, p. 181, and *Prof. Paper 75*, p. 97.

sideration of all factors; the probable errors are clearly stated—correct values probably within 5 to 20 per cent of the calculated figures.

CASE 3. THE METHOD WHEN NO CONSTANTS CAN BE ASSUMED

Many rocks are altered so fundamentally that no constituent or physical feature escapes modification. The analyses of fresh and altered rock may still be studied with some profit by graphic methods, as best developed by Leith and Mead (see later section).

THE METHOD OF SUCCESSIVE APPROXIMATIONS

HYBRIDS, CONTAMINATED ROCKS, AND ASSIMILATION

Problem 26.—Given the composition of the chilled base of the Sudbury lopolith, A, and that of the Missisagi quartzite, B, and *assuming* that the average composition of the whole mass, C, is a result of a mixture of the two,[1] how much of the quartzite has probably been added to 100 parts of the contaminated magma? Two methods of attack may be suggested.

1. The algebraic method starts with the equations $xA+yB=C$, and $x+y=100$; solving these equations for each constituent in the analyses gives a series of values for x and y. From an average of these the correct values can be approximated.

2. In contrast with this use of algebra, there is a method very useful in many petrologic calculations, which may be called the method of "successive approximations"—in popular slang it might be "Cut and Try."

Simple inspection of the main constituents in columns A, B, and C in Table I will suffice to show the student that equal parts of A and B will contain too much B to resemble the supposed mixture, C.[2] As an approximation then, the student should try adding 5 parts B to 10 parts A and dividing by 15 to reduce to percentages. This results in column X, and this also, as far as the main constituents are concerned, has too much quartzite to match column C. Since the error is not great, however, the next trial may well be 10 parts A plus 4 parts B (divided by 14 to reduce to percentages). This gives column Y, which is a fairly close approximation, some constituents indicating too much, and some too little, contamination. An

[1] This is a safer assumption for an approximate estimate of amount of assimilation than Bain's (*Journal of Geology*, Vol. XXXIII [1925], pp. 509–25).

[2] In minor constituents like the alkalies no mixture of A and B can equal C, but the error is probably no greater than the error in estimating the composition of A.

addition of about 40 per cent as much quartzite as magma is indicated, if assimilation of rocks like Missisagi quartzite caused the differences. These successive approximations require perhaps 30 minutes (or much less with a slide rule), and are much more to be trusted than some complex calculations assuming a constituent constant, or only slightly modified.[1]

TABLE I*

AN OUTLINE OF A CALCULATION CONCERNING ASSIMILATION

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2
1. Basal igneous rocks....	53.28	17.46	2.07	9.29	5.08	7.71	2.69	1.69	.73
2. 10 parts base.....	532.80	174.50	20.70	92.90	50.80	77.10	26.90	16.90	7.30
3. Quartzite†.....	89.42	5.82	.30	.97	.46	.15	.76	1.82	.17
4. 5 parts quartzite.....	447.10	29.10	1.50	4.85	2.30	.75	3.80	9.10	.85
5. 4 parts quartzite.....	357.68	23.28	1.20	3.88	1.84	.60	3.04	7.28	.68
6. Sum of 2 and 4.....	979.90	203.60	22.20	97.75	53.10	77.85	30.70	26.00	8.15
7. Sum of 2 and 5.....	890.48	197.78	21.90	96.78	52.64	77.70	29.94	24.10	7.98
8. =6 reduced to 100%..	65.33	13.57	1.48	6.52	3.54	5.19	2.05	1.73	.54
9. =7 reduced to 100%..	63.61	14.13	1.56	6.91	3.76	5.55	2.14	1.73	.57
10. Supposed mixture of two rocks.....	62.27	14.28	2.08	5.99	3.11	5.32	3.52	2.70	.73

	A Average Analysis Basal Phase	B Analysis of Missisagi Quartzite	X Mixture 10A+5B	Y Mixture 10A+4B	C Analysis of Igneous Rock Supposedly Contaminated by Assimilated Quartzite
SiO_2	53.28	89.42	65.53	63.61	62.27
Al_2O_3	17.46	5.82	13.57	14.13	14.28
Fe_2O_3	2.07	.30	1.48	1.56	2.08
FeO	9.29	.97	6.52	6.91	5.99
MgO	5.08	.46	3.54	3.76	3.11
CaO	7.71	.15	5.19	5.55	5.32
Na_2O	2.69	.76	2.05	2.14	3.52
K_2O	1.69	1.82	1.73	1.73	2.70
TiO_2	.73	.17	.54	.57	.73

* As a method of work most students find it easier to place the analyses in horizontal position. Multiplications or additions then give results lower down in the same column. For comparison of two analyses, however, most people prefer two vertical columns. Both arrangements are here shown, so that the student can get a clear idea of the work involved and of the value of this very useful method of calculation.

† Water omitted.

[1] The result is notably in disagreement with the results of Bain in the paper cited. While the quartzite here used in calculation is not the only formation near the magma, it is the only one for which Bain reported chemical data. More shaly sediments might be added in slightly larger amounts than 40 per cent; but it would be hard to find a mixture of normal sediments which could be added to norite in the amounts he suggests without making the norite abnormal. The normal character of the analysis in column *C* suggests an entirely different origin for the rocks found, as noted by Bowen in discussion, in *Journal of Geology*, Vol. XXXIII (1925), pp. 825–29.

GRAPHIC METHODS, TABLES, AND SHORT CUTS

There are several schemes in use for avoiding lengthy arithmetical calculations. Even in case the calculation is made, graphic methods and short cuts furnish a desirable check on the results.

Plots for use in microscopic work on the optical properties of minerals in general and plagioclase in particular were published by Wright.[1]

Possibly some methods of estimating mineral composition in rocks may be considered short cuts over the common Rosiwal measurements.[2]

Geographic tables and formulas are issued at times as bulletins of the United States Geological Survey.[3]

Tables for calculating rock analyses into molecular proportions, and these into mineral percentages, have been published in a number of places.[4] The use of such tables usually gives accurate values to two or three significant figures and some interpolation is possible. For more complete interpolation and probably more accuracy, the mineralogic scales and slide rules were invented, the circular rule being especially useful in estimating minerals from analyses or analyses from minerals.[5] It has been urged, however, that a brief table of mineral compositions and an ordinary slide rule serve the same purpose as the specially constructed instrument.[6]

[1] F. E. Wright, "Graphical Methods in Microscopical Petrography," *American Journal of Science*, Vol. XXXVI (1913), pp. 509–42.

[2] See A. Johannsen, "A Planimeter Method for the Determination of Percentage Composition of Rocks," *Journal of Geology*, Vol. XXVII (1919), pp. 276–85; "Shand's Recording Micrometer," *Journal of Geology*, Vol. XXIV (1916), pp. 394–401; and "Wentworth's Micrometer," *Journal of Geology*, Vol. XXXI (1923), pp. 228–32.

[3] *Bulletin 650* is the latest.

[4] J. F. Kemp, *School of Mines Quarterly*, Vol. XXII (1901), pp. 75–88, and *Handbook of Rocks;* A. Osann, *Beitrage zur chemischen Petrographie* (Stuttgart, 1903); Cross, Iddings, Pirsson, and Washington, *The Quantitative Classification of Igneous Rocks* (University of Chicago Press, 1903); A. Harker, *Tables* (Cambridge University Press, 1910); H. S. Washington, "Chemical Analyses of Igneous Rocks," *U.S. Geol. Survey Prof. Paper 99*, Appendixes 1–5, 1918; A. Holmes, *Petrographic Methods and Calculations* (Murby & Co., 1921); Harry von Eckmann, *Molekular Quotienten* (Upsala, 1925). (This table is based on atomic weights of 1911.)

[5] W. J. Mead, "Some Geologic Short-Cuts," *Economic Geology*, Vol. VII (1912), pp. 136–44.

[6] J. H. Hance, "Use of the Slide Rule in Computation of Rock Analyses," *Journal of Geology*, Vol. XXIII (1915), pp. 560–68.

Van Hise, in his "Treatise on Metamorphism,"[1] gave tables which he used in calculating changes in metamorphism. These include formulas, molecular weights, specific gravities, and molecular volumes.

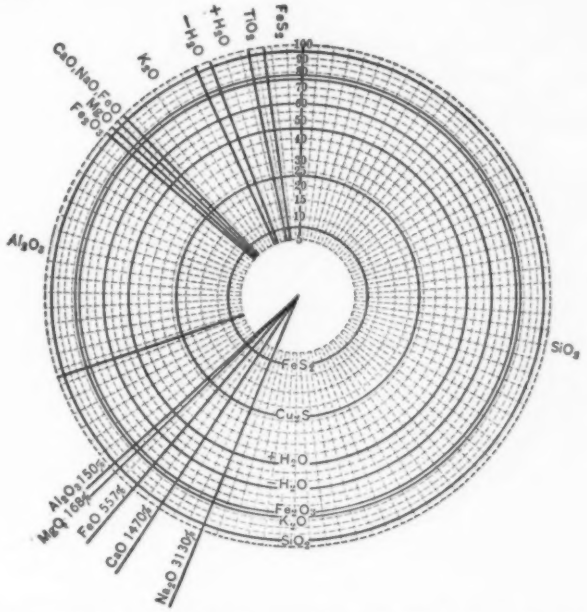

FIG. 4.—Chemical composition diagramof the fresh Clifton-Morenci porphyry and its thermally altered phase. After Steidtmann.

Leith and Mead give a graph for calculations involving the relation of specific gravity, porosity, and moisture of saturation.[2] At least one, and possibly several, of the methods of graphical representation of results for a report shown in the following section furnishes also some information as to the calculation itself (see Fig. 4).[3] Leith

[1] *U.S. Geol. Survey Monograph 47*, pp. 195–201.

[2] C. K. Leith and W. J. Mead, *Metamorphic Geology* (H. Holt & Co., 1915), p. 286, Plate XVI.

[3] Edward Steidtmann, "Alterations of Rocks by Weathering and by Hot Solution," *Economic Geology*, Vol. III (1908), pp. 381–409; Leith and Harder, "Iron Springs District, Utah," *U.S. Geol. Survey Bulletin 228* (1908), pp. 26–30.

and Mead also give a graphic method for finding about how much average sandstone, limestone, and shale can be derived from a given igneous rock, if analyses are available.[1]

When no information is available except the analyses of the fresh and altered rock, there are still methods of comparison which are instructive. The straight-line diagram (Fig. 5) and the circle devised by Ransome (Fig. 6) are much used even in the absence of any constant constituent or constant volume.[2] The change during

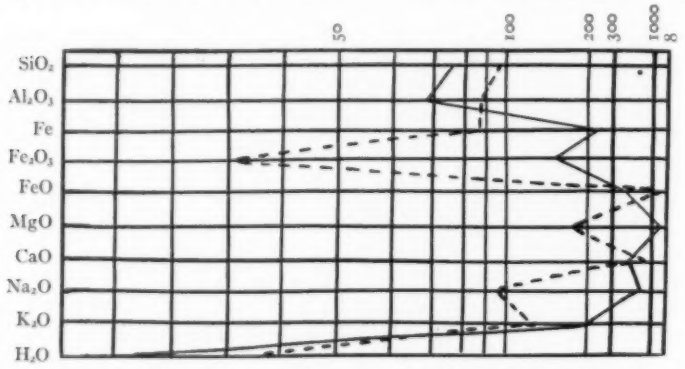

FIG. 5.—"Straight line diagram," showing gains and losses of several constituents, from the original taken as 100. In this form, the several constituents are each given a line, and one pair of rocks gives a series of points, connected by a zig-zag line. After Leith and Mead.

mineralization at Tonopah, Nevada, was shown by a series of diagrams of the type credited to Brögger[3] (Fig. 7), somewhat modified to include gangue minerals. Lindgren, after a review of the methods, concludes that the really most effective diagram to show each alteration is a group of curves, one for each constituent, using as abscissas the distance of the rock from some datum plane, and as ordinates, molecular ratios of the constituents.[4] (See Fig. 8, in which this form of diagram is used for a differentiated series of rocks.)

[1] *Op. cit.*, pp. 316–19.

[2] Leith and Mead, *Metamorphic Geology* (H. Holt & Co., 1915), p. 288; L. F. Reber "Mineralization at Clifton-Morenci," *Economic Geology*, Vol. XI (1916), p. 566.

[3] J. E. Spurr, "Geology of the Tonopah Mining District, Nevada," *U.S. Geol. Survey Prof. Paper 42* (1905), pp. 242–43.

[4] F. L. Ransome, "Geology and Ore Deposits of Breckenridge, Colorado," *U.S Geol. Survey Prof. Paper 75* (1911), p. 97.

CONDENSATION OF A CALCULATION FOR A REPORT

Arithmetic is so familiar that a technical report seldom includes the full detail of addition or multiplication. It is a difficult matter

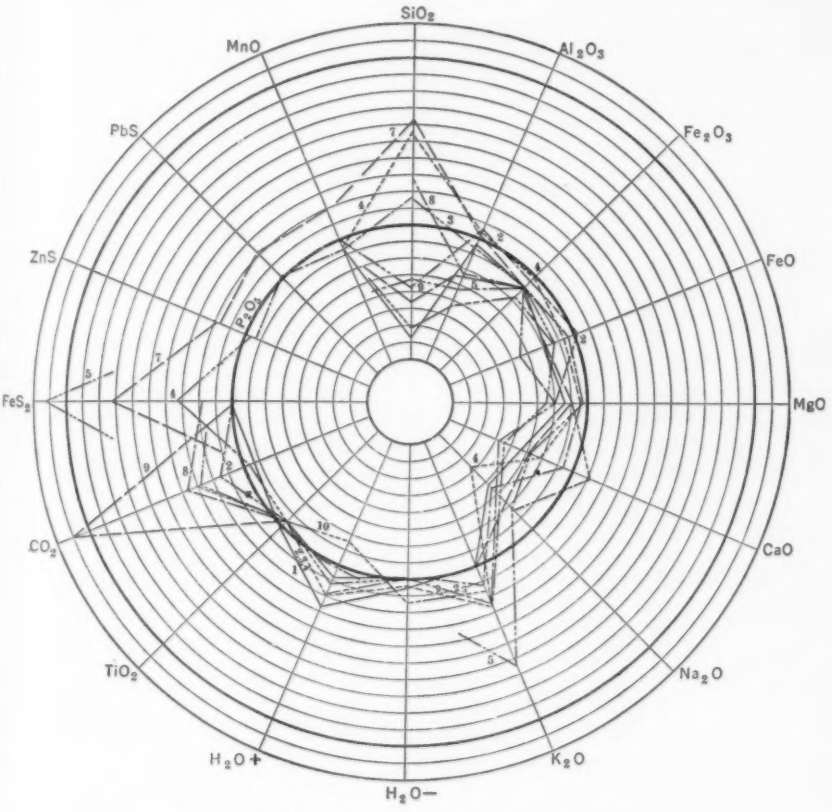

FIG. 6.—Sericitization and propylitization. After Reber

to decide, however, just how far to carry this elimination of detail in a reported calculation. Probably the safest rule here is to *show the data and state the method in sufficient detail so that the reader can duplicate the work* if he is interested. If the data used are not given in full, the sources and references should be clearly stated. In most

cases it is possible to indicate calculations by tabulating certain stages in the progress of the work (see Problem 26).

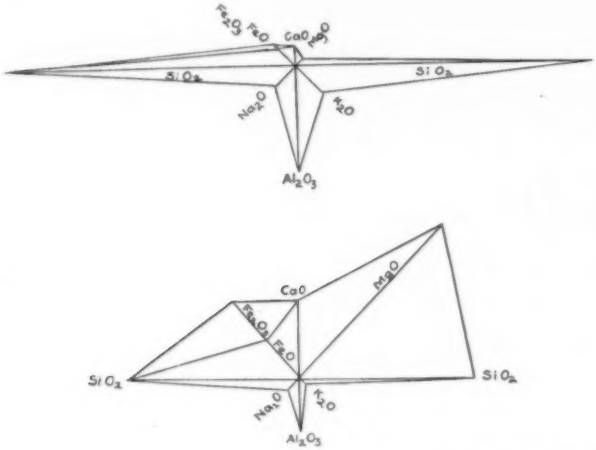

FIG. 7.—Diagrams illustrating the differing chemical compositions of rhyolite and peridotite. After Kemp. This style of diagram is credited to Michel-Levy, but has been modified successively by Brögger, Hobbs, and Spurr.

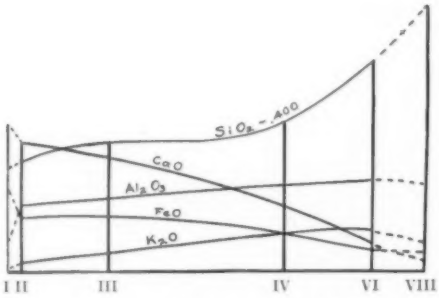

FIG. 8.—Diagram of the molecular ratios of some of the constituents of the rock series at Magnet Cove, Ark. Abscissas represent distances from the origin at II. After Washington.

Graphic methods of presentation of results are very useful, not only to save space, but to make an impression that is obtained only with difficulty from a study of a table. Where much depends on

the results, however, the graph should be accompanied by numerical tabulated data.

Probably the simplest graph used in petrography is that showing by divisions in bars the percentages of the mineral or chemical constituents, the total length of bar representing 100 per cent (Fig. 10). This has been used from early times[1] to the present day, and

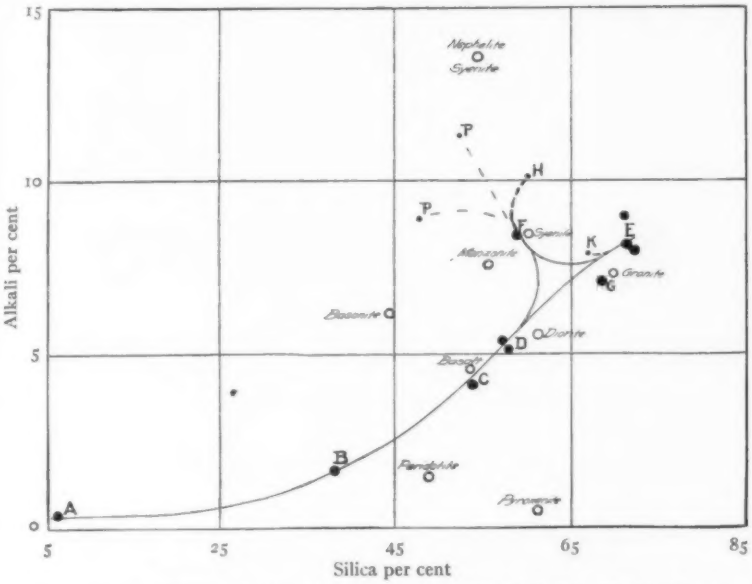

FIG. 9.—A diagram of the rock series of the Vermilion batholith. The black spots show rocks analyzed; the circles show the average compositions of several standard rock families for comparison.

while a single bar may represent a single analysis, a series of bars represents a series of rocks.

Iddings has reviewed the methods of showing the compositions of igneous rocks by diagrams,[2] of which there are a large number (see Fig. 11). A few of these are so constructed that a series of rocks may be shown in a diagram, but others show only one rock in a

[1] Rosenbusch is credited with an early one.

[2] J. P. Iddings, "Chemical Composition of Igneous Rocks Expressed by Means of Diagrams," *U.S. Geol. Survey Prof. Paper 18*, 1903.

diagram. It is possible to go even farther and diagrammatically compare one rock series with others (Fig. 9).[1]

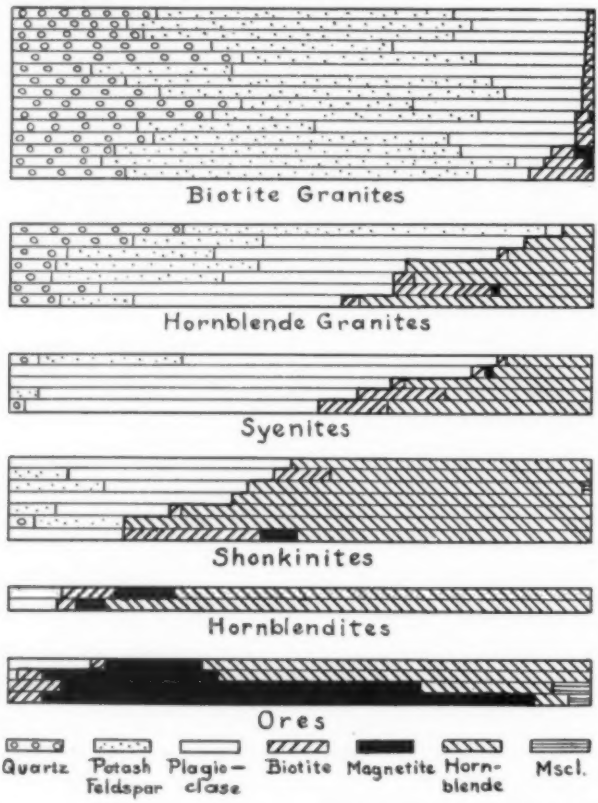

FIG. 10.—Diagram of the modes of the several phases of the Vermilion batholith. Each horizontal bar represents one rock measured.

The alteration of one rock to another of different composition (even with some intermediate steps) can be shown graphically in several ways, depending somewhat on the available data.

[1] Frank F. Grout, "A Graphical Study of Igneous Rock Series," *Bulletin Geological Society of America*, Vol. XXXIII (1922), pp. 617–38; and "The Vermilion Batholith of Minnesota," *Journal of Geology*, Vol. XXXIII (1925), p. 485.

When data are very complete as to volume and porosity, etc., or as to the constancy of a constituent, as well as composition, the addition and subtraction of various constituents can be shown by bars, lines, or points, one side or the other of base line or datum. A favorite method in some places is the so-called "straight-line diagram"[1] based on the ratios of the amounts of each constituent in

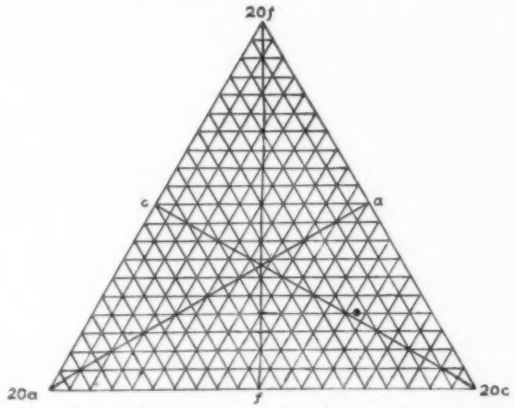

FIG. 11.—Graphical representation of a gabbro-diorite. After Osann

the altered rock to the amounts in the fresh rock. If these ratios ($\times 100$) are plotted along a straight-line scale, the relative behavior of the several oxides can be seen at a glance. If any constituent can assumed constant, those to the left of it have increased during be alteration, and those to the right, decreased. A logarithmic scale is most convenient. In studying a number of cases of alteration one may use as many horizontal lines as there are constituents. The identity of a particular pair of analyses can then be preserved by connecting the several points for that series of constituents with a zig-zag line, as in Figure 5. A somewhat more compact diagram showing such features uses a circle as the base line or datum, and plots the increase outside, and decrease inside along radii of the circle (Fig. 6).[2]

[1] W. J. Mead, "Some Geologic Short-Cuts," *Economic Geology*, Vol. VII (1912), pp. 136–44.

[2] F. L. Ransome, "Geology and Ore Deposits of Goldfield, Nevada," *U.S. Geol. Survey Prof. Paper 66* (1909), p. 181. L. F. Reber, in *Economic Geology*, Vol. XI (1916), p. 566, used it for a group of ten comparisons all at once.

PART III. SOME SUGGESTIONS BASED ON CALCULATIONS CONCERNING MAGMATIC DIFFERENTIATION

CALCULATIONS ON THE DIFFERENTIATION OF GRANITE FROM BASALT

The two main rock types of the world are basalt and granite, and some petrologists have had a strong tendency in recent years to regard granite as a differentiation product of basaltic magma.

Problem 27.—How much average granite can be derived from average basaltic magma without making the differentiated fractions abnormal. Two methods of attack have been suggested. The first is to take a definite bulk of average basalt and subtract average granite from it, noting whether the residue is analogous to any rock type. The second method is to subtract from average basalt the common differentiates of basaltic magma, and note whether any of them or any combination of them modifies the rock toward a granitic composition. Each of these involves successive approximations, rather than a formula. In these calculations the student starts with a subtraction from the original instead of an addition, as illustrated in Problem 26 on assimilation, but the calculation is otherwise very similar.

Method 1.—It is evident from a simple inspection of columns I and II, Table II, that not over three parts of basalt are needed to supply enough of each constituent so that one part of granite could be produced. The calculation then is a basis for deductive reasoning. Assume that one part of granite is separated from three parts of basalt, and test, by calculation, the consequences: in other words, see if the residue, or the other differentiate, has such a composition as might be expected. Column III is the result.

To judge whether column III is a reasonable composition it may be compared with any large compilation; but perhaps as good a test as any is a calculation of the norm from the analysis. The norm contains over 10 per cent nephelite. Since nephelite rocks are very much more rare than granites, it is unreasonable to assume that two parts of such nephelite rock are formed every time one part of granite is formed.

By supplying successively larger amounts of basalt until the removal of granite leaves a normal rock, it is found that nine parts

of basalt cannot furnish one part granite without producing a nephelite rock as residue; but ten parts of basalt will supply all the needed elements for granite and leave a residue that is not so peculiar as to create any doubt as to the probability of the process. In this case the residue is more like basalt than any other class of rocks. In other words, *if granite is to be produced from basaltic magma, so little granite will be formed from so much basalt that the residue will*

TABLE II

BASALT AND GRANITE RELATIONS

	I Average Basalt*	II Average Granite†	III ½(3 Basalt −1 Granite)	IV ½(9 Basalt −1 Granite)	V ½(10 Basalt −1 Granite)
SiO_2	49.06	69.92	38.63	46.45	46.74
Al_2O_3	15.70	14.78	16.16	15.82	15.80
Fe_2O_3	5.38	1.62	7.26	5.85	5.80
FeO	6.37	1.67	8.72	6.96	6.90
MgO	6.17	.97	8.77	6.82	6.75
CaO	8.95	2.15	12.35	9.80	9.70
Na_2O	3.11	3.28	3.02	3.09	3.09
K_2O	1.52	4.07	.25	1.20	1.24
H_2O	1.62	.78	2.04	1.72	1.71
TiO_2	1.36	.39	1.85	1.48	1.47
P_2O_5	.45	.24	.55	.48	.47
MnO	.31	.13	.40	.33	.33
Normative nephelite	none	none	11.50	.28	none

* Daly's *Igneous Rocks and Their Origin* No. 53, p. 27.
† Daly's, No. 4, p. 19.

be but slightly changed in character. As a maximum, *one-tenth of an average basaltic magma may become granite.*

Method 2.—Starting with average basalt, the student may subtract, successively, average peridotite, average pyroxenite, and any other early differentiates from basaltic magma that may be indicated by inspection of the residues, and then see if the residues approach the composition of granite (see Table III).

A simple inspection of the average basalt and average peridotite in Daly's compilation will show that the magnesia must be supplied in very notable amounts to produce peridotite. Ten parts basalt will not yield enough magnesia for two parts peridotite. Since this segregation is commonly considered as an important factor in the production of granite, it may be well to carry it about as far as

possible. Hence Table III starts with twenty parts basalt and subtracts three parts peridotite; then others. Evidently the main process of differentiation of basalt to granite is not a result of the segregation of extreme products. Such products of gabbro magma may be complementary to each other, but no combination of such products is complementary to granite.

TABLE III

BASALT AND THE EFFECT OF REMOVING SOME OF ITS EXTREME DIFFERENTIATES

	I Average Basalt	II 20 Parts Basalt − 3 Peridotite*	III Column II − 2 Pyroxenite†	IV Column III − 1 Average Ore‡	V Column IV − 5 Anorthosite§	VI Column IV − 8 Anorthosite
SiO_2	49.06	50.49	51.32	54.29	56.43	59.45
Al_2O_3	15.70	17.61	18.77	19.79	15.05	8.42
Fe_2O_3	5.38	5.62	5.32	3.48	4.83	6.72
FeO	6.37	6.23	6.04	4.70	6.69	9.48
MgO	6.17	1.57	.41	.17	deficient	deficient
CaO	8.95	9.75	9.00	9.29	7.54	5.07
Na_2O	3.11	3.57	3.95	4.22	4.53	4.95
K_2O	1.52	1.62	1.69	1.81	2.40	3.23
H_2O	1.62	1.28	1.30	1.34	1.67	2.14
TiO_2	1.36	1.40	1.27	.07	.04	deficient
P_2O_5	.45	.51	.57	.47	.71	1.03
MnO	.31	.35	.36	.37	.55	.80
	100.00	100.00	100.00	100.00	.....	.....

* Daly's, No. 70, p. 29.

† Daly's, No. 74, p. 30.

‡ Ore averaged from twenty-four analyses given by Iddings, *Igneous Rocks*.

§ Daly's, No. 63, p. 28.

It may be argued that peridotites of different composition might yield residues more closely resembling granite. This is no doubt true, but granite is too abundant to be explained as a residue from the formation of any exceptional rock. The average peridotite is the only proper basis of calculation.

OTHER PROBLEMS OF DIFFERENTIATION

The process of differentiation should, of course, not be considered as a clean-cut separation of gabbro and granite, even though the calculation given above considers only the two main products. Most differentiated masses that show good exposures of gabbro and granite show all gradations, and possibly some intermediate rocks develop in notable volume. For these it is easily possible to conduct a similar

calculation through intermediate steps. Starting with one hundred parts of basalt, one may find how much andesite or diorite can be derived from it. With that much diorite one can calculate how much quartz monzonite can be derived. With that much quartz monzonite one can find how much granite can be derived. The final result in terms of granite formed from basalt is much the same. The calculated differentiates are, roughly, as follows:

	Percentage
Olivine gabbro, gabbro, and minor segregations	80
Diorite	10
Quartz monzonite	5
Granite	5

This agrees in a general way with field observations on the amounts of aplite related to diabase intrusives.[1]

The suggestive calculations of this sort are numerous. Those concerned with the evolution from stony meteorite to basalt, from granite to nepthlite syenite, and the main course of differentiation from basalt to granite are most significant. The same general plan may be followed also in the study of particular districts.[2] In several the data are so complete that an average magma may be estimated (see Problem 12), and the separation of a series of differentiates produces a progressive change in the magma residue. Such cases give us our best data as to the actual processes of differentiation.

[1] R. A. Daly, *Journal of Geology*, Vol. XXVI, p. 119; N. L. Bowen, *op. cit.*, p. 69; W. H. Collins, *Geol. Survey of Canada, Memoir 53* (1913), p. 65; F. E. Wright, "Mount Bohemia," *Michigan Geol. Survey, Annual Report* (1908), p. 355.

[2] For Sudbury, see A. P. Coleman, "The Nickel Industry," *Bulletin Canada Department of Mines* (1913), pp. 104–8; Steinar Foslie, "Field Observations in Northern Norway," *Journal of Geology*, Vol. XXX (1921), pp. 709–12; W. H. Collins, "The Geology of Gowganda Mining Division," *Geol. Survey Canada, Memoir 33* (1913), pp. 72–83; L. V. Pirsson, "Igneous Rocks of the Highwood Mountains," *U.S. Geol. Survey Bulletin 237* (1905), pp. 171–201. For Duluth, see Frank F. Grout, "A Type of Igneous Differentiation," *Journal of Geology*, Vol. XXVI (1918), pp. 626–58; for Purcell sills, see R. A. Daly, "Geology of American Cordillera at the Forty-ninth Parallel," *Report of the Chief Astronomer, 1910*, Appendix No. 6 (1913), pp. 231–55; H. C. Cooke, "Gabbros of East Sooke," *Geol. Survey of Canada, Museum Bulletin No. 30*, 1919; A. Harker, "Carrock Fell," *Quarterly Journal Geological Society*, Vol. L (1895), pp. 311–37, and Vol. LI, pp. 125–48. For Assynt, see S. J. Shand, "On Borolanite," *Edinburgh Geological Society Transactions*, Vol. IX (1905–10), pp. 376–417; and A. Gemnell, "Chemical Analyses of Borolanite," *ibid.*, pp. 417–19; J. Volney Lewis, "Petrography of the Newark Igneous Rocks of New Jersey," *Geol. Survey of New Jersey, Annual Report for 1907*, pp. 120–33.

PROBLEMS IN ASSIMILATION AND SYNTECTIC DIFFERENTIATION

Daly has insisted that assimilation need not result in "obviously hybrid rock" as a common thing.[1] This may be checked by the student by means of a calculation of the same sort as that given for Sudbury norite (Problem 26), substituting the average analysis of any common igneous rock family, and the analysis of average shale or average sandstone. After the addition of large amounts of these sediments the analysis may seem to have some peculiar features, but none so peculiar that they are not found in igneous rocks not suspected of contamination. A further check on the reasonableness of the mixture as an igneous rock will be found in the calculation of a norm—it reveals no exceptional features. Additions of more than 100 per cent of these sediments may yield some evident hybrids.

The student may select analyses of rocks of particular districts, as well as the world-averages, for this study. Igneous rocks and sediments have been analyzed at several places.[2]

If the assimilation of limestone is similarly tested, the student will obtain rather different results from those in the case of sandstone and shale. Although limestone constitutes a small percentage of our sediments, its importance as a desilicating agent in magmas has been strongly maintained.[3] Daly estimates that the addition of 1 to 10 per cent of lime to a basaltic rock will have as much effect as in any rock yet discovered.

It should be noted that the desilication resulting directly from

[1] R. A. Daly, "Genesis of Alkaline Rocks," *Journal of Geology*, Vol. XXVI, p. 126.

[2] The Purcell sills were described by R. A. Daly in *Report of Chief Astronomer*, Ottawa, 1913.

Pigeon Point rocks were described by W. S. Bayley in *U.S. Geol. Survey Bulletin 109*. No assimilation of quartzite by gabbro could make red rock, but the amount of possible assimilation of quartzite in either igneous rock before the production of a conspicuous hybrid can be tested by the method here suggested.

The rocks of Gowganda were described by Bowen, including earlier analyses by Collins, in *Journal of Geology*, Vol. XVIII (1910), pp. 658–74.

The rocks near Huntly, Scotland, are described by H. H. Read, in *Geol. Survey of Scotland, Memoirs 86* and *96* (1923), p. 139.

The rocks of Marsco, Isle of Skye, were so studied by A. Harker in "Tertiary Igneous Rocks of Skye," *Memoir of Geol. Survey* (1904), pp. 184–85.

[3] R. A. Daly, *Igneous Rocks and Their Origin*, pp. 430–35; "Origin of the Alkaline Rocks," *Bulletin Geological Society of America*, Vol. XXI, pp. 87 et seq; "Genesis of Alkaline Rocks," *Journal of Geology*, Vol. XXVI (1918), pp. 131–32.

addition of lime is relatively slight, and such as might result from any other metallic oxide, without silica. All other constituents than lime are proportionately reduced as lime is added. There is no increase, for example, in the percentage of alkalies.

After additions of lime, however, a calculation of probable minerals indicates that some lime silicates might form early; if they settled out, the residue would be desilicated in a much more thorough way, and alkalies would be concentrated. This is an illustration of syntectic-differentiation. The steps in such a process may be studied by the use of average analyses.

Problem 28.—How much addition of average limestone to average basalt will make the late magma residue notably alkaline?

The average limestone[1] contains about 42.57 per cent of lime, equivalent to 76.02 per cent $CaCO_3$. The rest of the rock contains 5.19 per cent silica, so that it cannot be expected to have much effect as a desilicating agent. To simplify the work the student may well calculate the effect of adding CaO to various igneous magmas, remembering that assimilation involved in adding 10 per cent lime is about $23\frac{1}{2}$ per cent of average limestone. Daly's estimate that 10 per cent of lime is sufficient should not mislead anyone into thinking that only 10 per cent of rock is assimilated.

Table IV shows the results of "cut and try" additions of lime to average basalt. It is evident from the simplest inspection that lime is notably high in the contaminated rocks, but it is not difficult to find igneous rocks with equally high lime content which are not suspected of contamination. A more instructive test is a calculation of the norm.

Nearly 2 per cent of lime may be added to average basalt without any development of nephelite in the norm (column *B* of Table IV). The desilication is slight and there is a decrease in alkalies rather than any increase. There is no mineral change, suggesting that the addition should start a settling-out of calcium silicate. If such a settling occurred, the magma would be feldspathic, but not especially alkaline; with added lime the feldspar would actually be more calcic than before. The only argument for a notable decrease in silica or

[1] F. W. Clarke, "Data of Geochemistry," *U.S. Geol. Survey Bulletin 770* (1924), p. 34.

increase in alkali, when less than 4 per cent of average limestone is assimilated in basaltic magma, must be based on the rather uncertain "activity" of CO_2.

Additions of 5 to 15 per cent of lime (or 11 to 35 per cent of limestone) to basaltic magma produce considerable nephelite (columns *C* and *D*, Table IV). Any settling of the calcium silicate after such additions will leave a magma desilicated and enriched in nephelite. The addition of 10 per cent of lime changes a large portion of the

TABLE IV

BASALT PLUS LIME

	A Average Basalt*	X Composite Analysis of Limestone†	B Basalt Plus 2% CaO‡	C Basalt Plus 5% CaO‡	D Basalt Plus 10% CaO‡
SiO_2	49.06	5.19	48.10	46.72	44.60
Al_2O_3	15.70	.81	15.40	14.95	14.27
Fe_2O_3	5.38	.54	5.27	5.12	4.89
FeO	6.37	.....	6.24	6.07	5.79
MgO	6.17	7.89	6.05	5.88	5.61
CaO	8.95	42.57	10.73	13.29	17.23
Na_2O	3.11	.05	3.05	2.96	2.83
K_2O	1.52	.33	1.50	1.45	1.38
H_2O	1.62	.77	1.59	1.54	1.47
TiO_2	1.36	.06	1.33	1.30	1.24
CO_2	.....	41.54	.....	.....	.....
Others	.76	.25	.74	.72	.69
	100.00	100.00	100.00	100.00	100.00
Normative nephelite	none	.....	.14%	5.68%	12.21%

* From Daly's, No. 53, p. 27.

† From Clarke's *Bulletin 770*, p. 34.

‡ Equivalent to 100/42.57 times as much limestone. Each calculated mixture reduced to 100 per cent.

original albite to nephelite, but it is again to be noted that the addition of lime is not the process which enriches the rock in alkalies—quite the reverse. The enrichment comes only from the later separation of high-calcium rocks from the magma.

This leads to the further observation that the hybrid of basalt with 10 per cent lime contains over 17 per cent of lime, and that the derivation of a more alkaline rock from this requires a further concentration of this lime in a basal segregation. The syntectic differentiation of alkaline rocks from basalt magma, therefore, whether by 5 per cent or 10 per cent of added lime, probably involves the formation of equal amounts of high-calcium segregations. Few such rocks

are known and most of them seem related to gabbro rather than to nephelite rocks.[1] There are a few districts, however, where calcic rocks are associated with alkaline rocks as if in agreement with the theory.

Problem 29.—How much average limestone can be added to average granite before the magma is evidently hybrid or alkalic in its late residue?

Granite magma may assimilate limestone without forming any evidently hybrid minerals until assimilation is very large (see Table V). Ten per cent of lime, equivalent to 23 per cent average lime-

TABLE V

GRANITE PLUS LIME

	Average Granite	Granite + 10% CaO Reduced to 100%	Granite + 20% CaO Reduced to 100%
SiO_2	69.92	63.56	58.27
Al_2O_3	14.78	13.44	12.62
Fe_2O_3	1.62	1.47	1.35
FeO	1.67	1.52	1.40
MgO	.97	.88	.81
CaO	2.15	11.05	18.46
Na_2O	3.28	2.98	2.73
K_2O	4.07	3.70	3.40
H_2O	.78	.71	.65
TiO_2	.39	.35	.33
P_2O_5	.24	.22	.20
MnO	.13	.12	.11

stone, modifies a granite so far that 13 per cent of wollastonite appears in the norm. The mode, however, would probably include this lime in some normal cafemic mineral; and the added lime is not enough to use up all the quartz of the original; there is no shortage of silica and no increase in alkalies on account of the addition.

Even 20 per cent of lime (45 per cent average limestone) is not sufficient to combine with all the free quartz of average granite. Quartz is reduced and wollastonite constitutes nearly 30 per cent of the norm. The rock would probably be a syenite, rich in augite. If this augite largely settled out of the highly contaminated magma, the residual magma would still not be conspicuously alkaline.

[1] Some thirty-one analyses of the 4,980 superior analyses of fresh rocks in *Professional Paper 99* have as much as 17 per cent lime; almost half of them come from Uncompahgre, Colorado, or from the Ural Mountains, where they seem to be differentiates of normal gabbro.

It may be that in some particular calculation lime binds 2.5 times its weight of silica, as Daly says,[1] but when added to an average granite containing about 29 per cent of free quartz, 45 per cent of average limestone does not eliminate all of that 29 per cent quartz. There is neither nephelite nor acmite in the norm. The advocates of the production of alkaline rocks by such a syntectic-differentiation should show the calculation in detail.

THE THICKNESS OF EARTH SHELLS

There have recently been a number of papers describing definite shells with differing material in the earth. This is based on a very uncertain interpretation of earthquake data, and while it must be admitted that there are some other data and calculations that fall in line, still others are strongly opposed to any idea of such regularity as is implied in the term "earth shell." Without any exhaustive treatment of the matter, certain calculations place strict limits on the available material for the supposed shells.

From the results of the calculations previously given and others of similar nature, the amount of granite which can be formed from an original earth of such composition as meteorites can be calculated. If this amount is uniformly distributed as a shell in the lithosphere, its thickness can be estimated. The chief difficulty encountered in such a series of calculations is in the attempt to divide material like a stony meteorite into peridotite and basalt.[2] Some allowance must probably be made for the formation of deep-seated peridotite with a composition not quite like that of surface peridotites. Certain constituents such as potash and titanium are so low in meteorites and so high in known peridotites that very little peridotite of that sort could be formed.

Problem 30.—How thick a superficial shell of granite could be expected if the material of the earth is like that of meteorites?

By the method of successive approximations it can be found that, starting with the stony portion of meteorites, a separation of 70 per

[1] R. A. Daly, *Igneous Rocks and Their Origin*, p. 431.

[2] G. P. Merrill, in 1909, could not see the possibility that differentiation of such material as meteorites could form the variety of igneous rocks known at the surface of the earth (*American Journal of Science*, Vol. XXVII, p. 474).

cent of a peridotite not very different from average peridotite will leave 30 per cent of basalt with no conspicuous difference from average basalt. Any attempt to form much more basalt fails to yield reasonable compositions. Thirty per cent basalt is therefore a maximum, and since separation is probably not complete, 20 per cent basalt may be considered a reasonable estimate of the amount of basaltic magma ever separated from the deeper shells.

This layer assumed to result from differentiation of original stony meteorite material would not stop differentiating at the stage of basaltic magma. From an average basaltic magma the heavier olivine rock would settle and more siliceous and alkalic magma would rise. The basalt layer would probably be thus reduced (Problem 27) to 10 per cent of the lithosphere. Since the stony shells of earth have been estimated (Problem 15) as near 1,100 miles thick, the actual zone of basaltic composition in the earth may be expected to range from 75 to 150 miles in thickness, no doubt grading into the zones above and below it. More accurate calculations here, involving specific gravities of the several zones and their volumes, are not justified by the crude data and assumptions on which calculation is based.

Problem 27 indicates that the differentiation of all the possible basalt into an upper granitic zone would yield only 10 per cent as much granite as original basalt. If 20 per cent of the lithosphere can be separated as basalt, and only 10 per cent of that can be separated as granite, not over 2 per cent of the lithosphere can be granite. A granitic earth shell 20 miles (32 kilometers) thick is a maximum, on the assumptions here made; 10 miles (16 kilometers) is more likely.

This calculation from crude data to an uncertain result has the merit of being independent of, and based on wholly different facts from, some other estimates of the amount of granite and basalt in the shells of the earth. It may be noted, therefore, that Daly has tentatively placed the surface of the "basaltic substratum" at 40 kilometers below the surface, and estimated that the granitic shell may be of the order of 6 to 8 miles thick.[1] Holmes, in a more recent review of rock shells of the earth, prefers to estimate 25 to 30 kilo-

[1] Daly, *op. cit.*, pp. 215 and 248.

meters as the thickness of the granitic shell, at least in some continental areas;[1] Jeffreys suggests that rocks become basic at a depth not greater than 16 kilometers;[2] and Washington concludes the granitic earth shell is 15 to 20 kilometers thick.[3] If the available granite from a world-wide basaltic shell is somehow concentrated in the continental segments, as indicated by the densities, these estimates are not incompatible with the present calculation.

While the probable errors in the values here calculated are undoubtedly large because of the uncertain composition of the original material, there is no such uncertainty as to the ratios between granite and basalt. These are based on average compositions that may be taken as fairly close values. If the proportions of granite to basalt in the earth, or the amounts of granite actually found, do not fit calculated results, it would mean that the original assumption was in error. It would not, however, make it possible to derive any larger proportion of average granite from an average basaltic magma whatever the source of the basalt. Such limits furnish a much-needed check on speculations.

[1] Arthur Holmes, "Radioactivity and the Earth's Thermal History," *Geology Magazine*, Vol. LXII (1925), p. 532.

[2] Harold Jeffreys, *The Earth* (Cambridge University Press, 1924), p. 87.

[3] H. S. Washington, "Chemical Composition of the Earth," *American Journal of Science*, Vol. IX (1925), p. 354.

PETROLOGICAL ABSTRACTS AND REVIEWS

ALBERT JOHANNSEN
University of Chicago

BARTHOUX, JULES. "Chronologie et description des roches ignées du désert Arabique," *Mem. a l'Institute d'Egypte*, V (1922), pp. 264; 14 plates; 3 maps; 46 figs.

The term "Arabian Desert," as used in this report on its geology, is not the desert of Arabia, but embraces the region north of Nubia and east of the Libyan Desert. It is a region of igneous, sedimentary, and metamorphic rocks, and embraces most of the rocks of the normal alkali-lime series as well as some of the alkali series.

Following a short description of the geography of the region is a chapter on denudation and the alteration of the rocks. Then comes the description of the rocks themselves. The older sediments, lying upon the granite, are black, green, and red schists, conglomerates, and arkoses. They probably extend from late pre-Cambrian to Middle or Lower Silurian. Following their deposition came the slow rise of the Arabian Mountains. Folding is not complex. The age of the igneous intrusions cannot be exactly established, but preceding the green breccia came andesites, and following it, a second series of andesites, syenites, diorites, and a second granite. The Carboniferous is represented by a long series of sandstones, with interbedded basalt; the Jurassic, by calcareous argillites and sandstones with some volcanic rocks and tuffs at Ouadi Natasch. The Eocene and Miocene are largely calcareous rocks, with some basalts and tuffs, while the Pliocene consists of argillites and sandstones with some basalt. The final 125 pages are devoted to detailed descriptions of the igneous rocks. Thirty-six chemical analyses are given.

BARTRUM, J. A. "A Conglomerate at Onerahi, near Whangarei, Auckland, New Zealand," *Transactions New Zealand Institute*, LIII (1921), 128–30; 1 plate, showing six thin sections of rock.

Describes various pebbles of rocks which show evidence of having been subjected to far more pressure than any of the rocks of the basement complex of the island. This pre-Mesozoic land is believed to have been not wholly destroyed until after mid-Tertiary times.

BARTRUM, J. A. "Notes on the Geology of the Great Barrier Island, New Zealand," *Transactions New Zealand Institute*, LIII (1921) 115–27; 1 map; 6 plates.

Great Barrier Island consists of a basement complex of folded sediments, largely shales and greywackes, extending over approximately one-sixth of the northern part of the island. These rocks were eroded and are overlaid by Tertiary andesite, largely fragmentals with subsidiary lavas, which are probably well over 1,000 feet in depth. Overlying these are later acid volcanics. In the basement rocks were found conglomerate bands containing granite, pegmatite, and granulite. Dikes cutting the basal complex are much altered, but pegmatite, quartz-porphyry and quartz-porphyrite were found. Hutton originally (1869) described diorite as well, and later (1889), an elvanite.

BENSON, W. N., DUN, W. S., AND BROWNE, W. R. "The Geology and Petrology of the Great Serpentine Belt of New South Wales. Part IX. The Geology, Palaeontology, and Petrography of the Currabubula District, with Notes on Adjacent Regions." *Proceedings Linnean Society of New South Wales*. XLV (1920), 285–317, 337–74, 405–23.

Preceding papers, with the exception of Part VIII, have been reviewed in *Journal of Geology*, XXV (1917), 493–95, and XXX (1922), 174. In the present series Section A deals with the general geology of the region, Section B with paleontology, and Section C with petrography. The rocks of this region are in part alkaline, namely, soda rhyolites, keratophyres, and albitic dolerites, and in part calcic andesites and dolerites. Being connected by intermediate types, they are thought to have come from a common stock magma. Analyses are given of a trachytoid quartz keratophyre and of an andesitic pitchstone.

BEREK, M. *Mikroskopische Mineralbestimmung mit Hilfe der Universaldrehtischmethoden*. Berlin: Gebrüder Borntraeger, 1924. Pp. 168; 55 figs.; 7 plates.

This large book, devoted wholly to methods for the determination of the optical properties of minerals by means of the rotating stage, indicates the extent this method has grown.

Rotating stages of various types have been used in mineralogy at least since 1848, but it was not until 1891, when Fedorow began his work with a new type of stage, and especially since 1896, when he com-

menced his feldspar studies, that it attracted much attention. And even since that time the complex character of the instrument and the great time required in making determinations has kept it from general use. Fedorow himself said of some of the methods that the time required is too long to make them of much used in determinative work. There are, however, many determinations that can be made easily and quickly by means of this instrument, and in this book are brought together these methods, several of them, devised by Berek, entirely new. With the introduction of the large Leitz stage, it is now possible to use slides of ordinary size (28×48 mm.) instead of the original circular ones of Fedorow, so that it is unnecessary to have special sections made. It is true that special theodolite microscopes have been made, but these are expensive and usually not at hand.

While the petrographer ordinarily finds it necessary to determine only the kinds of minerals present in a rock, it may occasionally happen that he is called upon to determine the optical properties of a mineral in exact values, either of a new mineral or when he is making a detailed petrographic study of a region. For such work a Fedorow stage is of very great value, especially if the material is limited to thin sections, either because the material is too rare or of too small a size to isolate. With such a stage, the number of sections adapted for measurements is greatly increased, since many that are incorrectly oriented for ordinary use can be properly placed by rotation.

Besides the Russian works of Fedorow, Ussow, and Nikitin, there have been, aside from brief summaries in general textbooks such as Rosenbush-Wülfing or Johannsen, only the original articles by Fedorow in German and a translation of Nikitin's book by Duparc and Devries, and even these are now hardly up to date.

In the present book are given a number of new methods as well as those older methods which have been proved by the author to be serviceable. Among the former are those which Berek calls the method of characteristic extinctions (pp. 91–99) and the method of characteristic wave differences (pp. 108–27). Of the latter the author says it is the simplest as well as the one which will yield the best results, since it requires the measurement of only six to seven values of wave differences by means of the compensator. There is also given a method for determining the intermediate refractive index.

The book adds to our knowledge of the plagioclase feldspars. Several new diagrams and a number of new tables are given. The author makes the noteworthy statement (pp. 86 and 132) that he has found the plagio-

clases to vary in composition not only zonally, but in some cases which show no zonal growth at all, in adjacent twins. Here the adjacent lamellae show different chemical compositions, a remarkable condition for minerals of an isomorphous series, crystallizing simultaneously from a melt.

The book is so arranged that it should not be difficult to understand for any student who uses the petrographic microscope and knows the ordinary means of physical measurement. All mathematical demonstrations have been omitted from the part dealing with the methods, but they are brought together in the third part of the book.

The plates at the back show (I) a diagram for the calculation of $n \sin i = k$; (II) three figures showing (*a*) values of three principal values of double refraction in the plagioclases, (*b*) values of double refraction used in determining the optical character, (*c*) true values of the optic axes in the plagioclases; (III) the poles of the principal faces of plagioclases in a diagram whose co-ordinate axes are n_α, n_β, and n_γ instead of the crystallographic axes (therefore much better for optical determinations); (IV) directions of edges and normals of plagioclases on axes as in III; (V) maximum extinction angles in the symmetrical zone of the plagioclases; (VI) diagram for use in the method of characteristic extinctions; (VII) diagram for use in the method of characteristic wave differences.

The curves and values for the plagioclases differ somewhat from those given by Wülfing and from those given by Reinhard, but that is to be expected so long as the standard material is from natural crystals. No bibliographic references are given: the author speaks of the works of Fedorow, Ussig, and so on, and assumes that the reader is familiar with these works. Such references may be found in Wülfing, but it would seem desirable that here also the references should be given.

The book is of great importance and should be in the hands of every advanced student of petrology.

BERGT, W. "Der Vulkan Quilotoa in Ecuador und seine schiefrigen Laven," *Veröff. d. Städtischen Museums f. Länderk, Leipzig*, XIII (1914), 23–53; 8 plates; 1 map.

Describes the volcano Quilotoa in Ecuador, and its peculiar schistose dacite lava. An examination of the earlier work of Stübel and Reiss showed that there are lavas in numerous other places in Columbia and Ecuador, but these are eutaxitic or piperno-textured, owing to differences in mineralogical composition. The lava from Quilotoa shows no fracturing of the crystals, consequently the schistosity is not the effect of pressure subsequent to the extrusion, but it is primary and is due to

pressure and movement during crystallization. Here, then, is an example of primary parallel texture in an extrusive rock similar to that which is well recognized in the plutonites.

BOSWELL, P. G. H. "Some Aspects of the Petrology of Sedimentary Rocks," *Proceedings Liverpool Geological Society*, XIII (1923), 231–303.

This paper is the President's address to the Liverpool Geological Society. The first thirty-three pages are devoted to a summary of the existing literature on sedimentary petrography. Following this is a list of minerals that have been found in the sediments, a total of eighty-one, and of these thirty-six have been found in a single British locality. A list showing the geological time-range of certain minerals in British sediments is also given. Nine of the problems of sedimentary petrography are considered. A twenty-four page bibliography is added.

BOSWELL, P. G. H. "Some Further Considerations of the Petrology of Sedimentary Rocks" (presidential address), *Proceedings Liverpool Geological Society*, XIV (1924), 2–33.

This paper discusses the distribution of heavy minerals in British sediments, the constituent minerals, and the range of minerals in geological time, and gives information regarding rock history yielded by the minerals of sediments. A review of recent work with bibliography concludes the article.

BOWEN, N. L. "Genetic Features of Alnoitic Rocks at Isle Cadieux, Quebec," *American Journal of Science*, III (1922), 1–34.

In this paper are described certain rocks from the Isle Cadieux, near Montreal, which are monticellite-bearing alnoites. They differ from previously described alnoites in containing both ordinary olivine and monticellite, the latter hitherto considered a mineral only of contact metamorphism. The rock is dark grey, fine-grained and mottled with poikilitic biotites about 1 cm. in diameter. Other minerals are biotite, olivine, augite, melilite, perofskite, ore, apatite, marialite, and carbonates. The proportions of the minerals vary, but biotite is usually most abundant, though in some cases exceeded by melilite or ordinary olivine. Melilite varies from almost none to 30 per cent, augite up to 20 per cent, monticellite in amounts increasing as the augite increases, ordinary olivine from 10 to 35 per cent. In the specimen of the principal type analyzed,

the proportions by weight are; biotite, 30; monticellite, 25; chrysolite, 15; augite, 10; melilite, 3; apatite, 4; perofskite and ore, 7; carbonates, 6. (It is 4 1 6 of the reviewer's system). Patches and streaks in this rock consist principally of biotite and melilite, forming possibly a new type. The author says:

A study of the relations of the minerals indicates that the rock originally consisted of augite and chrysolite and was nearly completely consolidated as such. These minerals were then attacked, with lowering temperature, probably by their own interstitial liquid as it changed in composition, and were replaced by monticellite, melilite, and biotite with marialite, perofskite, and titaniferous magnetite as minor products of the reaction. The monticellite is itself replaced by melilite and biotite and the melilite-biotite rock is the end product of the replacement. The replacement was accomplished by an alkalic liquid [magma] which formed monticellite from augite by desilicating it, and later gave rise to melilite and the more definitely alkalic mineral biotite. . . . . In the experimental part of the paper, equilibrium in mixtures of nephelite and diopside is determined. It is found that from intermediate mixtures forsterite and melilite are the first products to crystallize. . . . . It is thus proved experimentally that nephelite reacts with diopside to form melilite, a reaction analogous to that which is considered to have taken place between augite and alkalic liquid in the natural rocks. This reaction is of the nature of a desilication of the diopside, and while the formation of monticellite in this manner has not been demonstrated in the relatively simple experimental mixtures, the demonstration of desilication of diopside in these mixtures is believed to give support to the idea that monticellite is so formed from augite in the more complex natural mixture. An outstanding difference between the natural, replacing liquid and the artificial mixtures is the presence of potash and water in the former. As a result of this difference the reaction products instead of being forsterite and melilite were, in the natural rock, biotite, and melilite with monticellite as an intermediate step. In fact chrysolite, originally present, was itself a principal source of biotite.

BRAUNS, R. "Die phonolitischen Gesteine des Laacher Seegebietes und ihre Beziehungen zu anderen Gesteinen dieses Gebietes," *Neues Jahrbuch B.B.*, XLVI, 1–116; 1 plate.

The phonolitic area of the Laacher Sea region is about 10 km. long, north to south, and 5½ km. wide. The alkalic rocks overlie steeply folded greywacke schists and slates of Lower Devonian age, and since there are no sediments older than Lower Devonian among the included fragments in the igneous rocks, it is assumed that the underlying rocks are crystalline schists.

The history of the region has already been briefly summarized else-

where (*Journal of Geology*, XXXII (1924), 337–39), and need not be repeated here.

In the present paper the phonolitic rocks of the region are described, some of them from specimens occurring only as included fragments in the extrusives. Among the rocks are noselite-phonolite, leucitophyre, melilite-nephelinite, tephrite, tinguaite, selbergite, schorenbergite, syenite, nephelite-syenite, noselite-syenite, cancrinite-syenite, calcite-syenite, riedenite, garnet-pyroxenite, pegmatite, leucite-tuff, noselite-phonolite-tuff, tephritic-tuff, palagonite-tuff, and crystalline schists. The histories of the names that have been applied to some of the more important rocks are given: for example, the rock called nosean-phonolite by Brauns passed through the stages: hornartigen Porphyr, Noseanphonolith, Nosean-Leucitgestein, Leucitphonolith, Leucitophyr, and Leucitit. Such changes show the need of more uniform nomenclature.

The rocks are described in great detail, and there are numerous chemical analyses of the rocks and of the component minerals. They have been recalculated into Osann's system, and in some cases into mineral molecule percentages also, but nowhere are the actual modes given.

An interesting rock is a calcite-syenite with calcite micropegmatitically intergrown with aegirite-augite and alkalia feldspar in such a way that it appears to be undoubtedly primary. Since Boeke has shown experimentally that calcium carbonate melts at a temperature of 1289° and a pressure of 100 atmospheres and recrystallizes from the melt, there appears to be no doubt that it is possible for it to form as a primary mineral in igneous rocks under certain conditions.

New names are selbergite for a leucite-noselite-tinguaite-porphyry, schorenbergite for a noselite-leucite-nephelite-rock and riedenite for a noselite-biotite-pyroxenite.

BRAUNS, RHEINHOLD. *Die Entstehung des Laacher Sees.* "Rheinische Heimatbücher." Bonn, 1922. Pp. 31; 4 figs.

A popular guide to the Laacher Sea region.

BRAY, HARRIET G., AND EMERY, ALDEN H. "Mineralization along the Dikes in Southern Vermont," *Ohio Journal of Science*, XXIII (1923), 83–88.

In a region predominantly of quartz-mica-schist there are innumerable dikes of quartz, quartz-feldspar, and diorite, the latter being the oldest. The first two especially are accompanied by extensive mineraliza-

tion, giving rise to hornblende, actinolite, tourmaline, biotite, muscovite, phlogopite, paratonite, pyrite, magnetite, ilmenite, and other minerals.

BROUWER, H. A. "Crystallization and Resorption in the Magma of the Volcano Ruang (Sangi Islands)," *Konink. Akad. Wetens. Amsterdam*, XXIII (1920), 1–9.

All of the lavas from Ruang are hypersthene bearing, most of them being hypersthene-augite-andesites, with a few hypersthene-augite-amphibole andesites and a single augite-hypersthene-amphibole-olivine-basalt. In these rocks xenoliths of older rocks containing more amphibole and olivine indicate the character of the minerals which were able to crystallize at greater depths.

BROUWER, H. A. "Sur les Domes Volcaniques des Volcans Actifs de l'Archipel Malais," *Zeitschrift für Vulkanologie*, VI (1921), 37–46; 5 plates.

BROUWER, H. A. *Geologische Onderzoekingen op de Sangi-Eilanden en op de Eilanden Ternate en Pisang*. 'Sgravenhage, 1921. Pp. 63; 4 maps; 2 profiles; 15 plates.

In the first part of the second paper here listed the rocks mentioned in the first paper are described in greater detail, as are the rocks of the islands Tagoelandang, Makaleni, and Mahengetang. The second part deals with the island Ternate, and the third with Pisang. There are a number of chemical analyses, and good photographs of the islands and of thin sections of the rocks.

BROWNE, W. R. "The Igneous Rocks of Encounter Bay, South Australia," *Transactions Royal Society of South Australia*, XLIV (1920), 1–57; 4 figs.; 4 plates.

There are two related series of igneous rocks at Encounter Bay, a plutonic series consisting of quartz-mica-diorite, granite, and albite-mica-syenite, and an intrusive series of uralitic "dolerites," potash-aplite, soda-aplite, and granophyre. A pneumatolytic phase gave rise to quartz-tourmaline nests in the other rocks, altered the soda granophyres in part to greisen, and impregnated the country rock in the neighborhood of the albite-syenite. The rocks are post-Cambrian and pre-Permocarboniferous, and probably intruded at the close of the Cambrian. Fractional crystallization and a sinking of the crystals, and complementary differ-

entiation or the splitting of a portion of the original magma into an acid and a basic fraction are the causes of the two different types of differentiation.

There are numerous analyses, and for most of the rocks the modes are given. The "porphyritic granite" from Granite Island is 227″. It is an adamellite, but belonging rather to the granodiorite family than to the granite family, since the plagioclase is in excess of the orthoclase. The quartz-mica-diorite is 228. The even-grained granite is 226, not far from 222. A comparison of the chemical analyses with the modes of these two granites shows that the microcline is microperthitic microcline with rather a constant content of plagioclase, giving or 65.7, ab 22.9, and an 11.4, which is very close to one from Finland given by Mäkinen, or 67.2, plag 32.8. A calculated mode, therefore, would be very incorrect for the true mode, unless allowance were made for the soda and lime included in the potash feldspar. For the red aplite both calculated and measured modes are given. They differ but slightly, and are 116′, an alaskite-aplite. The minor potash-aplite is also 116′. The soda-aplite is 118, or leuco-albite-tonalite-aplite.

BRYAN, W. H. "Geology and Petrology of the Enoggera Granite and Allied Intrusives," *Proceedings Royal Society of Queensland*, XXXIV (1922), 123–60; 3 plates.

The general geology of this region was published in *Proceedings Royal Society of Queensland*, XXVI, p. 141. In the present paper the petrology is taken up. Two main groups of rocks are described: granitic and granodioritic rocks, and rhyolitic intrusives. Of the former there are two phases, a gray and a pink. The pink phase appears to have broken through the gray. They are not the result of differentiation in place from the same magma. These rocks were followed by aplitic rocks and a final reversion to the gray phase. A third rock, the Enoggera granite, is thought to have been produced by a mixture of the two distinct types. It is thus a hybrid rock. Several chemical analyses are given.

BRYAN, W. H. "An Unusual Tourmaline-Albite Rock from Enoggera, Queensland," *Proceedings Royal Society of Queensland*, XXXV (1923), 48–60; 1 plate.

Describes a rock which occurs almost at the contact between the Enoggera granite and the Brisbane schist. It consists almost entirely of albite and tourmaline. It resembles the Brisbane schists, except that the

tourmaline takes the place of the mica while the albite proxies the quartz. The explanation given by the author is that "the micaceous parts of the schist have been metasomatically replaced by tourmaline, and the excess silica together with that of the quartz veins have been removed to be redeposited elsewhere. Following this alteration, albite was introduced from the granite and deposited among the veins vacated by the quartz and in any interstices in the matted tourmaline." An analysis is given. Mineralogically the rock belongs to 1112. Only one other similar rock is known, a tourmaline-albite rock from Cornwall, described by Flett.

DALE, T. NELSON. "The Commercial Granites of New England," *U.S. Geol. Survey Bulletin* 738, Washington, 1923. Pp. 488; 96 figs.; 34 plates.

This bulletin is a revised and abridged edition of Bulletins 313, 354, 404, and 484. The general treatment is the same as in the former reports, but the descriptions of quarry plants have been omitted. By combining all the previous work, much duplication in the general treatment was avoided. Brought up to date and condensed, the material is in much better form for a general survey of the granite industry of New England.

DALY, R. A. "The Geology of American Samoa," *Carnegie Institute Publication* 340 (Washington, 1924), pp. 95–143; 9 plates; 1 fig.; 2 maps.

Tutuila and the Manua subgroup of islands, Tau, Ofu, and Olosega, were studied. The latter three are essentially basalt. In Tutuila basalt predominates, but there are alkalic trachytes, trachyandesites, and trachydolerites which are regarded as differentiates from it. Olivine gabbro is also present. The basalt has the composition of the average basalt of Hawaii. Part of the Pioa dome of Tutuila is a quartz-bearing trachyte. The sequence of eruption in these islands is basalt, trachyte, basalt. A number of analyses of igneous rocks is given.

DALY, R. A. "The Geology of Ascension Island," *Proceedings American Academy of Arts and Science*, LX (1925), 1–80; 8 figs.; 20 plates; 1 map.

Ascension Island is volcanic and consists of olivine basalt, olivine-free basalt, trachydolerite, trachyandesite, alkali trachyte, and alkali quartz-trachyte, essentially the same as in Tutuila, Samoa. A number of

fresh volcanic cones are filled with trachyte, and the author discusses the possible origin of this rock from basalt. Seven new rock analyses are given.

VON ECKERMANN, HARRY. "The Rocks and Contact Minerals of the Mansjö Mountain," *Geol. Fören. i Stockholm Förhand.*, XLIV (1922), 203–410; 109 figs.; 5 maps.

This elaborate report on the rocks and contact minerals of Mansjö Mountain simply covers an area of some 4,000 square meters on the crest of the mountain. The earth was removed in several hundred places, diamond drillings were made, and the vegetation cleared from an old quarry, making possible very detailed mapping.

The rocks consist of a synclinal series of limestones and gneisses which were intruded by amphibolites before the folding, and by harzburgite and probably also by eulysite, later. The harzburgite has a border of a pyroxene rock where in contact with the sediments, but a thin zone of hornblendefels against the basic rocks. The pyroxene rock is thought to have been formed by a hydatogenic enrichment at the contact. The eulysite is considered a hydatogenic, halogenic, pegmatitic residual solution from a basic magma whose aggregate crystallization resulted from suddenly decreased pressure following its intrusion. The main mass of the northeastern part of Mansjö Mountain is a white gneissoid granite, from which apophyses extend into the limestone. Here are found diopside, phlogopite, chondrodite, scapolite, vesuvianite, wollastonite, and a new fluor-pyroxene to which the name mansjöite is given.

There are very many analyses both of rocks and of minerals. The modal percentages of the former are given, and the descriptions of both minerals and rocks are very complete.

VON ECKERMANN, HARRY. "The Rocks and Contact Minerals of Tennberg," *Geol. Fören. i Stockholm Förhand.*, XLV (1923), 465–537; 11 plates; 1 map (Section I).

This paper describes an extremely interesting case of a large limestone xenolith, some 20×65 meters on the surface, inclosed in granite. Between the two rocks there is a contact zone showing at least four distinct and different zones. The block apparently fell into a hydatogenic magma inside a solidified or extremely viscous casing. The first change to take place was an assimilation of CaO by the granite and the formation of wollastonite and diopside around the contact. At the same time the bio-

tite of the normal granite here crystallized as hornblende. The granite was enriched in lime, as is shown by a plagioclase-quartz zone immediately adjacent to the granite, and between the two zones described are zones of vesuvianite and of garnet rock, the former nearer the limestone.

The paper describes the changes which have taken place and all of the minerals are described optically. There are eight new mineral analyses, four of granite, the latter at distances varying from 1 to 250 meters from the contact, and one of the plagioclase-quartz contact rock. A new formula for the constitution of vesuvianite is given.

VON ECKERMAN, HARRY. *Molekular Quotienten*. Upsala, 1925. Pp. 219.

In this table of molecular proportions, calculated to four places and giving the values for all percentages to the second decimal place, the atomic weights of 1911 have been used instead of the approximate values used by Osann and C.I.P.W.

GRUBENMANN, U., AND NIGGLI, P. *Die Gesteinsmetamorphose. I. Allgemeiner Teil*. Berlin: Gebrüder Borntraeger, 1924. Pp. 539; 160 figs.

This third edition of *Die kristallinen Schiefer* of Grubenmann has been so completely rewritten and revised that it bears very little resemblance to the former editions and might well be considered a new book. The fact that this first general part has been expanded to 539 pages indicates the extent of the revision. When Professor Grubenmann died, the manuscript of this part was in the hands of the printer, consequently it had his approval and was in accord with his latest views.

The book is divided into three general parts under the headings "The Original Material and Its Specific Characteristics," "The Reformation of the Material by Metamorphism," and "The Products of Metamorphism." The second subdivision especially has been very greatly changed from former editions, particularly in the presentation of the physico-chemical principles which underlie metamorphism.

Under the first division there is a section devoted to the geological, chemical, mineralogical, and structural characteristics of the original rocks from which the metamorphics were derived, as well as others devoted to the original sediments and their characteristics and to original composite rocks. The second division embraces the general principles of

rock metamorphism under the headings of static metamorphism and kinetic metamorphism, and deals in part with the phase rule and equilibrium. Under the head "Kinds of Metamorphism" are given autometamorphism, allometamorphism, contact metamorphism, and combined metamorphism. The second variety is subdivided into geothermal and dislocation metamorphism. Contact metamorphism is subdivided into thermal, pneumatolytic to hydrothermal metamorphism, and injection to assimilation metamorphism.

The products of metamorphism are grouped as of the kata-, meso-, and epi-zones, and there is a chapter on the structures, textures, and associations of metamorphic rocks.

Finally, there is a list of the metamorphic rocks, with short definitions giving the mineral contents, a list of various metamorphic minerals with their chemical compositions, and three indexes: author, subject, and of analyses.

The method used for recalculating the rocks is the same as that previously used by Niggli in his *Gesteins- und Mineralprovinzen*. It was given in detail in a review of that book in the *Journal of Geology*, XXXII (1924), 339–43. It is a pure chemical classification and resembles Osann's in some ways. It can be used for igneous, metamorphic, and sedimentary rocks, and analyses computed in it may be represented graphically. The original chemical analyses of most of the computations are not given, making it difficult, in cases where there are a number of analyses of similar rocks, to locate the rock, even when the bibliographic reference is given.

As was Niggli's former book, so is this also a very important contribution to petrology. It should form part of the working library of every advanced student of the science.

REVIEWS

Quantitative Mineralogical Analysis of Rock-Dusting Materials and Survey of Some Coal-Measure Shales of Western Pennsylvania. By A. H. EMERY and R. DE CHICCHIS. With chapter on "Chemical Analysis of Rock-Dusting Materials," by W. A. SELVIG. Bulletin 21, Mining and Metallurgical Investigations under Auspices of Carnegie Institute of Technology, U.S. Bureau of Mines, and Mining and Metallurgical Advisory Boards. Pittsburgh, 1925. Pp. 77.

From time to time there arrive for review publications of the United States Bureau of Mines on the use of stone dust as a preventive of coal-dust explosions in coal mines. There is a certain irony in the fact that the organization (then the Technologic Branch of the U.S. Geological Survey) which originally attempted to suppress this line of investigation when hit upon by one of its own investigators, is now the very organization that is pushing it as one of its chief lines of endeavor.

On December 6, 1907, mines Nos. 6 and 8 of the Fairmont Coal Company at Monongah, West Virginia, were the scene of a terrible coal-dust explosion which cost the lives of 361 miners, making it the worst disaster in the history of American coal mining up to that time. A prompt field and laboratory investigation of the results of that explosion fortunately revealed the fact that a sufficient quantity of finely divided shale, which may be picked up by the explosion wave, is capable of snuffing out a coal-dust explosion. As the most promising clue yet obtained, the investigator proposed to follow it up vigorously with the hope of soon being able to save life and property. But from the report which the present reviewer submitted to the Technologic Branch of the Survey, the censor blue-penciled the thirty pages pertaining to the shale-dust discovery, and thus sacrificed the chief fruits of the whole study. In its denatured form what remained appeared as *Bulletin No.* 383 of the U.S. Geological Survey in 1909 and was reprinted in 1911 as *Bulletin No.* 26 of the U.S. Bureau of Mines.

For the general flavor of this affair, together with some of the deleted portions of the report, the reader is referred to an editorial by T. C. Chamberlin: "Are There Line Fences in Science?" *Journal of Geology,*

Vol. XVIII (1910), p. 764–76. During the years that have since elapsed, *Bulletin 26* has nearly always been left out of the bibliographies which appear in each of the later bulletins of the series, even from those treating of the same general subject. This may possibly be because *Bulletin 26* has long been out of print, but it can still be found in various libraries. The volume under review does not differ from many others by the Bureau of Mines in making no reference to this work, but states that "Garforth, from his observations in the Altofts Colliery, England, was the first (in 1908) to suggest the systematic application of rock dust to prevent explosions." This may well have been the case, but the editorial by T. C. Chamberlin quotes three pages (*Journal of Geology*, Vol. XVIII, pp. 766–68) from the report of progress submitted to Washington by the reviewer on February 15, 1908. In these pages the rôle played by the shale-dust was clearly presented and strongly emphasized, and one of the obviously many possible ways of utilizing it in coal mines was pointed out.

It is of little moment that the Bureau thus lost a part of its own legitimate prestige in the new movement, but it is of consequence that the policy followed, by delaying for a considerable length of time the application of this effective remedy, has probably been the occasion of greater loss of life and destruction of property than need have been. It is thus felt that a certain amount of publicity given to the methods which made this possible may be worth while.

The method of checking coal-dust explosions by rock dusting has proved effective and has already saved many lives, just as was predicted that it almost certainly would early in 1908. This bulletin presents results of some of the most recent work in this field.

R. T. C.

The Stratigraphy of the Mississippian Formations of Iowa. By FRANCIS M. VAN TUYL. *Iowa Geological Survey*, Vol. XXX, pp. 33–374.

The Mississippian section of Iowa and the adjacent portion of Illinois has been considered standard for the lower series of that system since the comprehensive work of James Hall in his report on *The Geology of Iowa*, published in 1858. Later work has introduced some refinements in the interpretation of the section, but all of the stratigraphic units were fairly well recognized by Hall. Some of the formation names in the section were first used by him, these being Burlington, Keokuk, and Warsaw. The name St. Louis had been proposed at an earlier date by Engelmann, and Kinderhook was used by Meek and Worthen only a few years after the

appearance of Hall's report. The Spergen formation has been fully recognized and defined only in comparatively recent years. The name Ste Genevieve was proposed many years ago by Shumard, but only in late years has it been revived and brought into general use.

Hall's study of the stratigraphy in different parts of Iowa was not in sufficient detail to permit him to establish in an entirely satisfactory manner the exact lines of demarcation between the several formations, and a number of unconformities in the higher portion of the section, now recognized, were overlooked in the earlier investigations. Hall's paleontological studies sufficed to establish the general features of the succession of faunas in the section, but his collections of fossils were far too limited to permit him to present data showing the full range of the fossil species.

In the report which is presented by Dr. Van Tuyl an attempt has been made to bring together as much detailed information concerning the Mississippian of Iowa as could be gathered during the time at his disposal. He has assembled and correlated the observations of earlier workers, and has added a vast amount of detail gathered by himself from field and laboratory studies spread over the years 1913 to 1917. The several formations are more clearly defined and delimited than has been done before. Many local sections have been carefully measured, studied, and described, and innumerable fossil collections have been made with accurate stratigraphic data. These collections have all been listed, and from this information the stratigraphic range of the species of the several faunas has been accurately established.

Detailed faunistic, paleontological work of this sort is of the highest value in connection with studies devoted to the correlation of formations of similar age in other portions of the Mississippi Valley and also in regions more remote. No attempt has been made to constitute a paleontologic monograph, and neither old nor new species have been described, although four plates of fossils have been included in the report to illustrate a few of the more outstanding of the species of the several faunas.

Following the several chapters devoted to the consideration of the stratigraphy and the faunistic paleontology, a chapter is devoted to the geodes of the Keokuk and Lower Warsaw beds. These Keokuk geodes have long been objects of interest to students of geology and mineralogy, and Dr. Van Tuyl has brought together whatever information regarding them has been published in the past and has added to this the results of his own observations.

The closing chapter of the report gives an exceedingly brief description of the geological history as suggested by the stratigraphic and

paleontologic studies. As a whole, the work is an admirable contribution to the geology of Iowa and undoubtedly will prove to be of great service to workers elsewhere.

S. W.

Geology in Its Relation to Landscape. By JUNIUS HENDERSON. Boston: The Stratford Company, 1925. Pp. 152, figs. 94. $2.50.

This book consists of a series of charming essays upon the geologic processes and agents which fashion the surface features of the earth. By skilful delineation of the operating processes the author brings the reader to an appreciation of many of the beauties of Nature, which can only be appreciated, in the highest sense, by being understood. The poetry of landscape-building and landscape-carving is brought within the reach of anyone who will read these pages.

R. T. C.

Géologie Stratigraphique. By MAURICE GIGNOUX. Paris: Masson et Cie, 1926. Pp. 575, 124 figs. 60 francs.

This volume is essentially a concise treatise on the stratigraphic development of Europe, though here and there a small amount of space is devoted to other parts of the globe. It would seem to the reviewer to constitute a very convenient book of reference on the stratigraphy and the related phases of the geology of Europe.

R. T. C.

Panorama of Physiographic Types. By A. K. LOBECK. Madison, Wisconsin: Wisconsin Geographic Press. 4 page text; 2 charts, each 1 ft. by 1 ft. 6 in.

Each chart of Lobeck's *Physiographic Types* consists of a contour map showing a wide range of forms and a block diagram presenting the same forms in perspective with a geologic section. To a layman in perspective drawing, such as the writer, the charts fulfil their purpose with admirable clarity and thoroughness. Embracing, as they do, all well-recognized land forms, they should be of service in the classroom.

The text ably supplements the charts, and the two are closely correlated by a number scheme. Under the heading "Rocks," the relation of land forms to materials is presented, and the character and history of specific land forms is arranged under the classic titles, "Constructive

Forms" and "Destructive Forms." The discussion is concise and thorough. A few non-physiographic statements need revision. For example, ". . . . quartz . . . . is virtually the same as glass." "When . . . . the edge of a formation comes to the surface of the ground, the direction in which it trends across the country is known as its strike." Another departure from the straight and narrow way consists in substituting "lime" for lime carbonate.

Both text and charts are supplemented by exercises for students. These are mostly interpretive or deductive in nature, and range in difficulty from elementary map-reading to placing geologic colors on the land forms of the charts. The fact that some of the exercises could not be worked out from the text and charts, while a few are not physiographic, may be unsatisfactory to some teachers. Most of the exercises stick to the subject. The others had best be left to other courses. Some of the latter type lead the student into debatable inferences, and show the pitfalls of the deductive method. A case in point is the question, "Why are such mines often deep, much deeper than coal mines?" The deep mines referred to are mines in crystalline rocks.

The exercises are after all only a minor part of Lobeck's publication, and the individual teacher can revise them to suit himself. From the teaching standpoint, it may be regrettable that they are not worked out with greater thought, since exercises for students seem to be a relatively neglected phase of classroom literature when compared with the descriptive and expository texts now available in geology. There seems to be a real opening for exercises which would give the student more of the mental experiences of the field geologist: observation, comparison, correlation, inductive reasoning, the framing and testing of hypotheses. Exercises which would stress doing more than learning and which would give the student more of the joy of search and discovery, the elation of the pioneer, should find a hearty response.

EDWARD STEIDTMANN